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The Environments of Short-Duration Gamma-Ray Bursts and Implications for their Progenitors

Edo Berger^{a,*}

^a*Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02139, USA*

Abstract

The study of short-duration gamma-ray bursts (GRBs) experienced a complete revolution in recent years thanks to the discovery of the first afterglows and host galaxies starting in May 2005. These observations demonstrated that short GRBs are cosmological in origin, reside in both star forming and elliptical galaxies, are not associated with supernovae, and span a wide isotropic-equivalent energy range of $\sim 10^{48} - 10^{52}$ erg. However, a fundamental question remains unanswered: What are the progenitors of short GRBs? The most popular theoretical model invokes the coalescence of compact object binaries with neutron star and/or black hole constituents. However, additional possibilities exist, including magnetars formed through prompt channels (massive star core-collapse) and delayed channels (binary white dwarf mergers, white dwarf accretion-induced collapse), or accretion-induced collapse of neutron stars. In this review I summarize our current knowledge of the galactic and sub-galactic environments of short GRBs, and use these observations to draw inferences about the progenitor population. The most crucial results are: (i) some short GRBs explode in dead elliptical galaxies; (ii) the majority of short GRBs occur in star forming galaxies; (iii) the star forming hosts of short GRBs are distinct from those of long GRBs, and instead appear to be drawn from the general field galaxy population; (iv) the physical offsets of short GRBs relative to their host galaxy centers are significantly larger than for long GRBs; (v) there is tentative evidence for large offsets from short GRBs with optical afterglows and no coincident hosts; (vi) the observed offset distribution is in good agreement with predictions for NS-NS binary mergers; and (vii) short GRBs trace under-luminous locations within their hosts, but appear to be more closely correlated with the rest-frame optical light (old stars) than the UV light (young massive stars). Taken together, these observations suggest that short GRB progenitors belong to an old stellar population with a wide age distribution, and generally track stellar mass. These results are fully consistent with NS-NS binary mergers and rule out a dominant population of prompt magnetars. However, a partial contribution from delayed magnetar formation or accretion-induced collapse is also consistent with the data.

Keywords: gamma-ray burst, progenitor, host galaxy, neutron star binary

1. Introduction

Gamma-ray bursts (GRBs) are short, intense and non-repeating flashes of γ -ray radiation originating at cosmological distances. While GRBs exhibit a broad diversity in their prompt γ -ray emission (e.g., duration, spectral shape, peak energy, brightness), they can still be divided into two basic categories: short-duration and long-duration with a separation at about 2 sec (Kouveliotou et al., 1993). The short GRBs have durations as short as ~ 10 msec, while the long events extend to hundreds of seconds. In addition, short GRBs tend to exhibit harder γ -ray spectra than the long-duration events, and generally have a lower fluences.

The basic bimodality of GRB durations provided an early clue that the progenitors of the two classes are likely to be distinct. Within the broad range of possible scenarios, two popular models have emerged: The collapse of rapidly-rotating massive stars (“collapsars”; (MacFadyen and Woosley, 1999)) in the case of long GRBs, and the coalescence of compact object binaries (with neutron star and/or black hole

constituents – NS-NS/NS-BH; (Eichler et al., 1989; Paczynski, 1991; Narayan et al., 1992)) in the case of short GRBs. The key attractions of this mapping are the potential for a large energy release from both progenitor classes, and the expected typical timescale for each progenitor: A free-fall timescale of $t_{ff} \approx 30 \text{ s } (M/10 M_{\odot})^{-1/2} (R/10^{10} \text{ cm})^{3/2}$ for collapsars, and a dynamical timescale of milliseconds for the compact merger remnants of neutron stars and black holes. However, other progenitor systems have also been proposed for short GRBs, for example magnetars, thought to be the power source behind soft γ -ray repeaters (Thompson and Duncan, 1995), accretion-induced collapse (AIC) of neutron stars (Qin et al., 1998), and delayed magnetar formation through binary white dwarf mergers or white dwarf AIC (Levan et al., 2006; Metzger et al., 2008).

Until a decade ago, the distances, energy scale, geometry, environments, and progenitors of GRBs, as well as the relation between the two burst classes, remained uncertain due to the lack of precise positions. The discovery of long-wavelength, long-lived “afterglows” from long GRBs in 1997 provided the first glimpse at these properties (Costa et al., 1997; Frail et al., 1997; van Paradijs et al., 1997). Indeed, the sub-arcsecond positions enabled by long GRB afterglow detections

*Corresponding author

demonstrated a cosmological origin (Metzger et al., 1997), an energy scale of $\sim 10^{51}$ erg (Frail et al., 2001; Berger et al., 2003a,b; Bloom et al., 2003), significant collimation ($\sim 10^\circ$ jets; (Harrison et al., 1999; Stanek et al., 1999)), and direct evidence for relativistic expansion (Taylor et al., 2004). Intense afterglow and host galaxy observations also linked long GRBs with the deaths of massive stars, mainly through their exclusive location in star forming galaxies (e.g., (Bloom et al., 1998; Djorgovski et al., 1998; Fruchter et al., 1999)), their strong correlation with the rest-frame ultraviolet (UV) light of their hosts (Bloom et al., 2002; Fruchter et al., 2006), and their association with Type Ic core-collapse supernovae (Hjorth et al., 2003; Stanek et al., 2003).

The afterglows of short GRBs were discovered only in 2005. Prior to that point only a few afterglow searches were possible due to the relative faintness of the γ -ray emission, and hence a low event rate and large and delayed error circles (Hurley et al., 2002). In retrospect, these searches were woefully inadequate, reaching only about 21 mag at $\delta t \approx 1$ day in the optical and ~ 0.5 mJy at $\delta t \approx$ few days in the radio. The launch of NASA's *Swift* satellite in late 2004, provided the first chance for rapid and accurate positions for short GRBs, and indeed led to the detection of the first X-ray (Gehrels et al., 2005; Bloom et al., 2006), optical (Fox et al., 2005; Hjorth et al., 2005), and radio (Berger et al., 2005) afterglows in 2005.

As in the case of long GRBs, the determination of accurate positions revolutionized the study of short GRBs. First, it led to an association with galaxies at cosmological distances (e.g., (Berger et al., 2005; Fox et al., 2005; Hjorth et al., 2005; Bloom et al., 2006; Prochaska et al., 2006; Berger et al., 2007)) and hence an energy scale of $\sim 10^{49} - 10^{52}$ erg (assuming isotropy) (Berger, 2007; Nakar, 2007). Second, it led to the association of some events with elliptical galaxies pointing to an old progenitor population (Berger et al., 2005; Gehrels et al., 2005; Bloom et al., 2006). Third, it demonstrated that the afterglow emission is similar to that of long GRBs, albeit with a generally lower luminosity (Berger et al., 2005). Finally, it provided a rough estimate of the short GRB event rate (Nakar et al., 2006).

Despite these fundamental results the progenitors of short GRBs remain unidentified at the present. The key observational test of the NS-NS/NS-BH merger model, the detection of coincident gravitational waves, is at least several years away. Similarly, theoretical predictions of early optical/UV emission from an accompanying “mini-supernova” (Li and Paczyński, 1998), caused by the ejection of radioactive material from the merging system, are highly uncertain, and even the most optimistic predictions lead to a faint and rapidly-fading signal that may be challenging to detect. Thus, the most promising avenue for progress at the present comes from statistical studies of the environments of short GRBs, both on galactic and sub-galactic scales (e.g., (Prochaska et al., 2006; Berger, 2009; Fong et al., 2010)). These studies benefit from many of the same techniques that linked long GRBs with the death of massive stars, and allow for comparison with theoretical predictions.

In this review, I present the current state of our knowledge about the redshift distribution of short GRBs, the demographics

and detailed properties of their host galaxies, and their locations within their hosts. The structure of this review is as follows. In §2 I summarize the discovery of short GRB afterglows, and the subsequent identifications of their host galaxies and redshifts; the detailed properties of the hosts (luminosities, metallicities, star formation rates, masses, stellar population ages) are discussed in §3 and §4; in §5 I discuss the sub-galactic environments of short GRBs, utilizing mainly high-resolution *Hubble Space Telescope* observations; I discuss the possibility of large progenitor offsets (due to kicks or globular cluster origin) in §6; and finally, in §7 I use these results to place constraints on the progenitor population.

2. The Discovery of Short GRB Afterglows, Host Galaxies, and Redshifts

The discovery of short GRB afterglows starting in May 2005 led to the first identifications of their host galaxies and hence to distance measurements. The first short GRB with an afterglow detection, GRB 050509B, was localized to a positional accuracy of about $5''$ with the *Swift* X-ray Telescope (XRT) (Gehrels et al., 2005; Bloom et al., 2006). No optical or radio emission was detected. The X-ray error circle appeared to coincide with the outskirts of an elliptical galaxy at $z = 0.226$ (Gehrels et al., 2005; Hjorth et al., 2005; Bloom et al., 2006), with a probability of chance coincidence of $\sim 10^{-3}$. However, the error circle contained additional fainter galaxies possibly at higher redshift.

Only two months later, GRB 050709 was the first short burst localized to sub-arcsecond precision through the detection of X-ray (with *Chandra*) and optical emission (Fox et al., 2005; Hjorth et al., 2005). The resulting afterglow position coincided with the outskirts of an irregular star forming galaxy at $z = 0.161$ (Fox et al., 2005; Covino et al., 2006). Despite the on-going star formation activity within the host galaxy, the burst was not accompanied by a supernova explosion, indicating that the progenitor was not likely to be a massive star (Fox et al., 2005; Hjorth et al., 2005). However, due to the presence of active star formation, an association with a young progenitor system such as a magnetar could not be excluded.

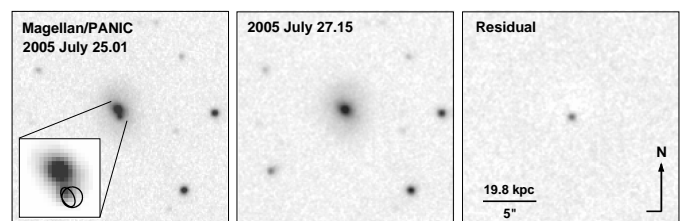


Figure 1: Discovery images of the near-infrared afterglow of GRB 050724 and its elliptical host galaxy. The inset shows the Very Large Array radio position (ellipse) and the *Chandra* X-ray position (circle). This was the first short burst to unambiguously establish a link with an old stellar population. From Berger et al. (2005).

It was only 15 days later that the discovery of X-ray, optical, and for the first time radio afterglow emission finally established a direct link between a short GRB and an old

stellar population (Berger et al., 2005; Barthelmy et al., 2005; Gorosabel et al., 2006). The afterglow of GRB 050724 was localized to an elliptical galaxy at $z = 0.257$ with no evidence for star formation activity ($\lesssim 0.05 M_{\odot} \text{ yr}^{-1}$) and with a stellar population age of $\gtrsim 1$ Gyr (Berger et al., 2005; Prochaska et al., 2006). The absence of both star formation activity and an associated supernova demonstrated a direct link to an old stellar population (Berger et al., 2005).

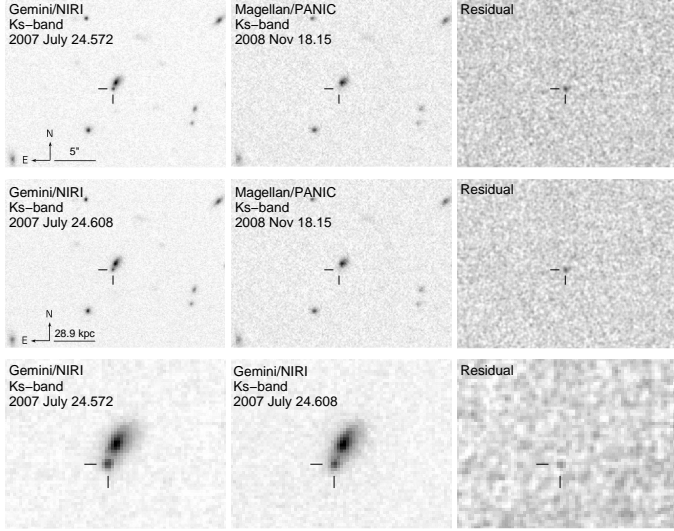


Figure 2: Discovery images of the near-infrared afterglow of GRB 070724 and its star forming host galaxy. Each row shows an afterglow image, a subsequent template image, and a residual image. The fading afterglow coincides with the disk of the host galaxy. From Berger et al. (2009).

The combination of low redshifts ($z \sim 0.2$) and the apparent dominance of elliptical galaxies in the first few short GRB hosts led to initial speculation of a particularly old progenitor population: $\tau \gtrsim 4$ Gyr (Nakar et al., 2006), $\tau \gtrsim 7$ Gyr (Zheng and Ramirez-Ruiz, 2007), and $\tau \gtrsim$ several Gyr (Gal-Yam et al., 2008). Indeed, a possible inconsistency with the expected merger time delay distribution of NS-NS binaries was noted (Nakar et al., 2006), although subsequent population synthesis models of NS-NS binary formation and mergers led to opposite claims (Belczynski et al., 2006). Clearly, the sample of short GRBs with afterglow detections available when these various claims were published was very small (GRBs 050509B, 050709, 050724, and 051221A).

Fortunately, the continued detection of short GRBs (mainly, though not exclusively by *Swift*), coupled with a community-wide concerted effort to discover and study their afterglows, led to a substantial increase in the sample of events over the past 5 years (e.g., Figures 2 and 3). Studies of this sample have led to a re-evaluation of the host galaxy demographics and the redshift distribution (e.g., (Berger et al., 2007)). In particular, as of late 2010, the sample of short GRBs with X-ray detections (positions of $\sim 2 - 5''$ radius) numbers about 40. Of these, about 20 events have been detected in the optical/UV/near-IR and/or radio, leading to positional uncertainties of $\sim 0.1 - 0.5''$. Host galaxies have been identified for nearly all of the bursts with sub-arcsecond positions (15/20), and putative hosts have

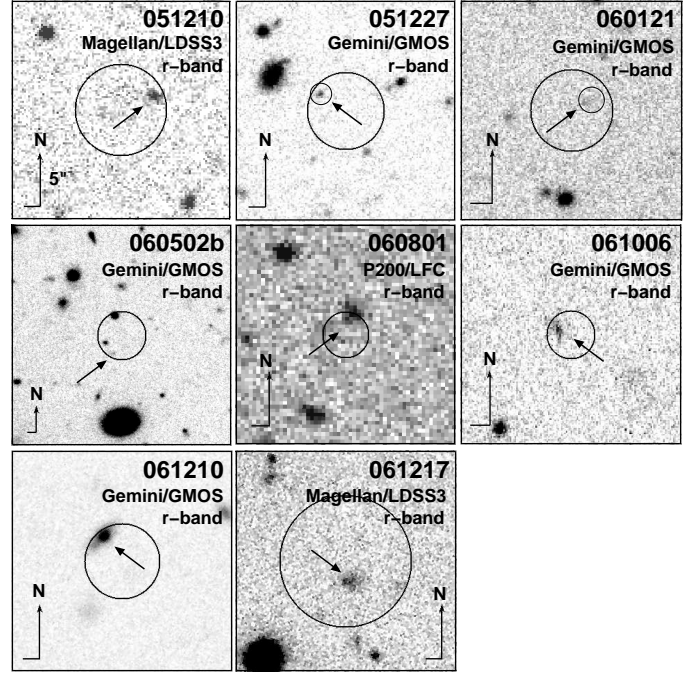


Figure 3: Ground-based images of several short GRB hosts obtained with the Magellan 6.5-m telescopes and the Gemini 8-m telescopes. All images are $20''$ on a side, with the exception of GRB 060502b which is twice as large. The large circles mark the XRT error regions, while smaller circles mark the positions of the optical afterglows (when available). Arrows mark the positions of the identified hosts. From Berger et al. (2007).

also been identified for a substantial fraction of the bursts with only X-ray positions (when deep searches have been made). At the present, 16 redshifts have been measured between the two samples (Figures 4 and 5).

The events with only X-ray positions have two shortcomings. First, the probability of chance coincidence for the typical host magnitudes within the XRT error circles ($\sim 21 - 26$ mag) is $\sim 10^{-3} - 1$. Second, in some cases there is disagreement about the position and radius of the XRT error circles between various groups, leading to systematic uncertainties in host associations. Luckily, in the subsequent discussion of detailed host properties no substantial difference in the sample with and without optical afterglows is found, suggesting that any spurious galaxy associations are at most a minor contaminant.

Using optical follow-up observations of nine short GRBs with X-ray and/or optical afterglows (available by the end of 2006), Berger et al. (2007) found that eight of the nine bursts were likely associated with much fainter galaxies ($R \sim 23 - 26$ mag) than the first few events. By comparison to this early sample (with $R \sim 17 - 22$ mag and $z \lesssim 0.5$), as well as the hosts of long GRBs and large field galaxy samples, it was demonstrated that these new host galaxies likely reside at $z \sim 1$ and beyond. A specific early case for a $z \gtrsim 1$ origin was GRB 060121 based on afterglow photometric redshift estimates (de Ugarte Postigo et al., 2006; Levan et al., 2006). Spectroscopic redshifts for the four *brightest* galaxies in this expanded sample led to measurements of $z \approx 0.4 - 1.1$ (Berger et al., 2007); see Figure 4. Subsequent observations have con-

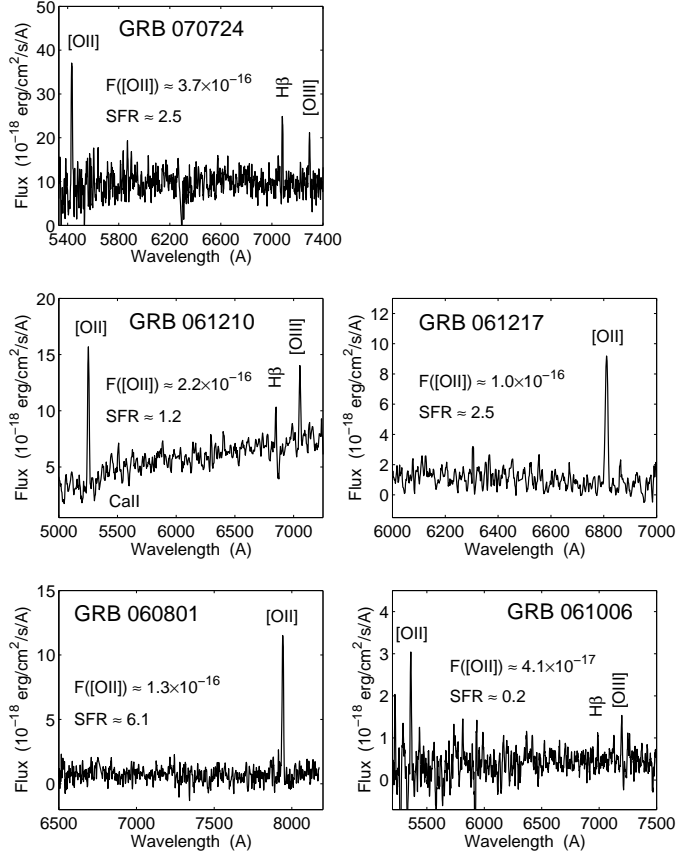


Figure 4: Optical spectra of several short GRB host galaxies. The relevant emission lines are marked and lead to redshifts of $z \approx 0.4 - 1.1$. Also indicated are the star formation rates inferred from the luminosity of the [OII] λ 3727 doublet. From Berger (2009).

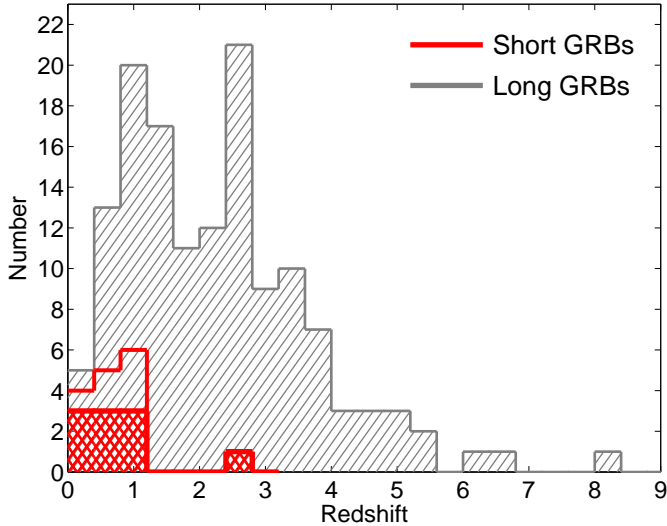


Figure 5: The redshift distributions of long (gray) and short (red) GRBs as of late 2010. The cross-hatched region indicates the redshifts for short GRBs with sub-arcsecond positions, while the open histogram includes the redshifts for host galaxies identified in some XRT error circle ($\sim 2 - 5''$ radius).

firmed a broad range of redshifts (e.g., (Graham et al., 2009; Antonelli et al., 2009; Levesque et al., 2010)), and the current

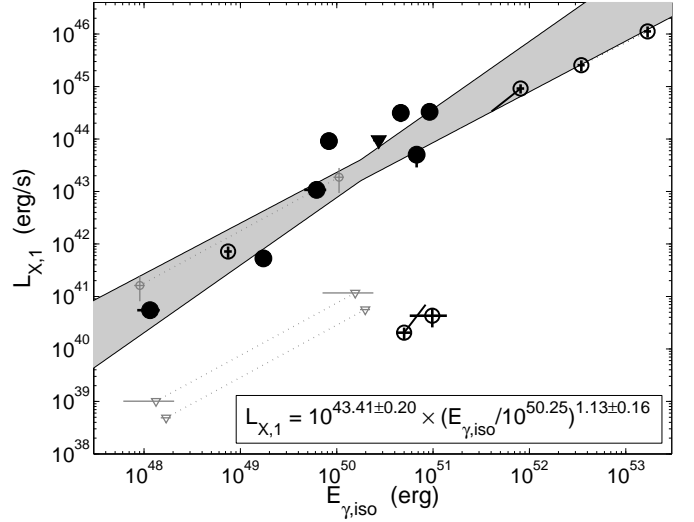


Figure 6: X-ray luminosity of short GRB afterglows normalized to $t = 1$ day (a proxy for the afterglow kinetic energy, $\epsilon_e E_{K,iso}$) plotted as a function of $E_{\gamma,iso}$ for events with a known redshift (solid black circles), redshift constraints (open black circles), and without any redshift information (gray symbols connected by dotted lines for $z = 0.1$ and 1 , corresponding roughly to the lowest and highest redshifts securely measured to date). The isotropic-equivalent relativistic energies are as least as high as 10^{51} erg, and may approach $\sim 10^{53}$ erg for some short bursts. From Berger (2007).

redshift distribution (in comparison to that of long GRBs) is shown in Figure 5.

One of the crucial ramifications of the measured redshift distribution is the energy budget of the γ -ray emission and blast-wave. In Figure 6 I show the isotropic-equivalent afterglow X-ray luminosities of short GRBs as a function of their isotropic-equivalent γ -ray energies. The former is a proxy for the afterglow kinetic energy (Kumar, 2000; Freedman and Waxman, 2001; Berger et al., 2003a). I find that both quantities span several orders of magnitude, with $E_{\gamma,iso} \approx 10^{48} - 10^{53}$ erg (although most short bursts have values of $10^{50} - 10^{51}$ erg). This range is similar to that for long GRBs (Frail et al., 2001; Berger et al., 2003a,b; Bloom et al., 2003), and indicates that either short GRBs can truly produce a broad range of energies, or instead exhibit a wide range of collimation angles. Due to the general faintness of short GRB afterglows, strong evidence for collimation exists in only one case (Soderberg et al., 2006; Burrows et al., 2006), but additional cases are possible (Berger, 2007).

3. Host Galaxy Luminosities, Metallicities, and Star Formation Rates

The secure association of at least one short GRB (050724) with an elliptical galaxy (Berger et al., 2005; Barthelmy et al., 2005; Gorosabel et al., 2006) demonstrated unambiguously that some of the progenitors are related to an old stellar population. However, as discussed in the previous section, a substantial fraction of short GRBs (1/3 – 2/3) reside at higher redshifts than initially suspected, $z \sim 1$ (Berger et al., 2007), and spectroscopic observations indicate that most of these galaxies

are undergoing active star formation (Figure 4; (Berger et al., 2007; D’Avanzo et al., 2009; Graham et al., 2009)). Indeed, in the sample of short GRBs localized to better than a few arcseconds about 50% of the bursts occur in star forming galaxies compared to only $\approx 10\%$ in elliptical galaxies; the remaining $\approx 40\%$ are currently unclassified due to their faintness, a lack of obvious spectroscopic features, or the absence of deep follow-up observations. This result raises the question of whether some short GRBs are related to star formation activity rather than to an old stellar population, and if so, whether the star formation properties are similar to those in long GRB host galaxies. The answer will shed light on the diversity of short GRB progenitors.

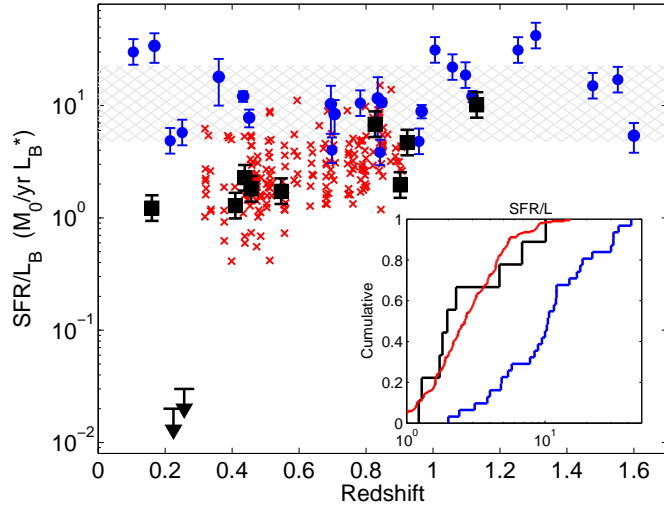


Figure 7: Specific star formation rates as a function of redshift for the host galaxies of short GRBs (black squares), long GRBs (blue circles) and field galaxies from the GOODS-N survey (red crosses; (Kobulnicky and Kewley, 2004)). Upper limits for the elliptical hosts of GRBs 050509B and 050724 are also shown. The cross-hatched region marks the median and standard deviation for the long GRB host sample. The inset shows the cumulative distributions for the three samples. The K-S probability that the short and long GRB hosts are drawn from the same distribution is only 0.3%, while the strong overlap with the field sample leads to a K-S probability of 60%. From Berger (2009).

In the following discussion, I compare several aspects of short and long GRB host galaxies: Luminosities, metallicities, and star formation rates. A comparison of the masses and stellar population ages is carried out in the subsequent section. For the current sample of short GRB hosts, the distribution of absolute rest-frame B -band magnitudes (M_B) ranges from about 0.1 to a few L_* (Berger, 2009; Prochaska et al., 2006). The star formation rates (mostly inferred from the $[\text{OII}]\lambda 3727$ line using the standard conversion (Kennicutt, 1998); Figure 4) range from about 0.1 to $10 M_\odot \text{ yr}^{-1}$ for the star forming hosts (Berger, 2009; D’Avanzo et al., 2009). In the case of the elliptical hosts the upper limits are $\lesssim 0.1 M_\odot \text{ yr}^{-1}$ (Berger et al., 2005; Bloom et al., 2006; Prochaska et al., 2006; Berger, 2009). Combined with the absolute magnitudes, the specific star formation rates (SSFR) are $\text{SFR}/L_B \approx 1 - 10 M_\odot \text{ yr}^{-1} L_*^{-1}$ for the star forming hosts, and $\lesssim 0.03 M_\odot \text{ yr}^{-1} L_*^{-1}$ for the elliptical hosts. The SSFR values as a function of redshift are shown in Figure 7.

For five¹ host galaxies in the current sample, there is also sufficient spectral information to measure the metallicity (Berger (2009); Prochaska et al. (2006); D’Avanzo et al. (2009)). I use the standard metallicity diagnostics, $R_{23} \equiv [(F_{[\text{OII}]\lambda 3727} + F_{[\text{OIII}]\lambda 4959, 5007})/F_{\text{H}\beta}]$ (Pagel et al., 1979; Kobulnicky and Kewley, 2004) and $F_{[\text{NII}]\lambda 6584}/F_{\text{H}\alpha}$. The value of R_{23} depends on both the metallicity and ionization state of the gas, which is determined using the ratio of oxygen lines, $O_{32} \equiv F_{[\text{OIII}]\lambda 4959, 5007}/F_{[\text{OII}]\lambda 3727}$. I note that the R_{23} diagnostic is double-valued with low and high metallicity branches (e.g., (Kewley and Dopita, 2002)). This degeneracy can be broken using the ratio $[\text{NII}]/\text{H}\alpha$ when these lines are accessible. To facilitate a subsequent comparison with field galaxy samples I use the R_{23} , O_{32} , and $[\text{NII}]/\text{H}\alpha$ calibrations of Kobulnicky and Kewley (2004). The typical uncertainty inherent in the calibrations is about 0.1 dex.

Adopting the solar metallicity from Asplund et al. (2005), $12 + \log(\text{O}/\text{H}) = 8.66$ Berger (2009) find $12 + \log(\text{O}/\text{H}) \approx 8.6$ for the upper R_{23} branch and $\approx 8.0 - 8.5$ for the lower branch for the host of GRB 061006. For the host of GRB 070724 they find $12 + \log(\text{O}/\text{H}) \approx 8.9$ for the upper branch, and $\approx 7.6 - 8.1$ for the lower branch. A similar range of values is found for the host of GRB 061210, but the ratio $F_{[\text{NII}]/F_{\text{H}\alpha}} \approx 0.2$, indicates $12 + \log(\text{O}/\text{H}) \gtrsim 8.6$, thereby breaking the degeneracy and leading to the upper branch solution, $12 + \log(\text{O}/\text{H}) \approx 8.9$. For the host of GRB 051221A (Soderberg et al., 2006), similar values to those for the host of GRB 070724 are inferred. Finally, for the host galaxy of GRB 050709, the $[\text{NII}]/\text{H}\alpha$ ratio indicates $12 + \log(\text{O}/\text{H}) \approx 8.5$. The dominant source of uncertainty in this measurement is the unknown value of O_{32} , but using a spread of a full order of magnitude results in a metallicity uncertainty of 0.2 dex. For the hosts with double-valued metallicities (GRBs 051221A, 061006, and 070724) I follow the conclusion for field galaxies of similar luminosities and redshifts that the appropriate values are those for the R_{23} upper branch (Kobulnicky and Kewley, 2004). This conclusion was advocated by Kobulnicky and Kewley (2004) based on galaxies in their sample with measurements of both R_{23} and $[\text{NII}]/\text{H}\alpha$. It is similarly supported by our inference for the host galaxy of GRB 061210. Future near-IR spectroscopy covering the $[\text{NII}]$ and $\text{H}\alpha$ lines will test this hypothesis. The metallicities as a function of host luminosity are shown in Figure 8.

To place the host galaxies of short GRBs in a broader context I compare their properties with those of long GRB hosts and field star forming galaxies from the GOODS-N survey (Kobulnicky and Kewley, 2004). In terms of absolute magnitudes, the long GRB hosts range from $M_B \approx -16$ to -22 mag, with a median value of $\langle M_B \rangle \approx -19.2$ mag ($\langle L_B \rangle \approx 0.2 L_*$; (Berger et al., 2007)). Thus, the long GRB hosts extend to lower luminosities than the short GRB hosts, with a median value that is about 1.1 mag fainter. A K-S test indicates that the probability that the short and long GRB hosts are drawn from

¹A sixth host, GRB 071227, has an inferred metallicity of about $0.4 - 1 Z_\odot$, but this was inferred in the absence of detected hydrogen Balmer lines (D’Avanzo et al., 2009), and the values are therefore prone to large systematic errors.

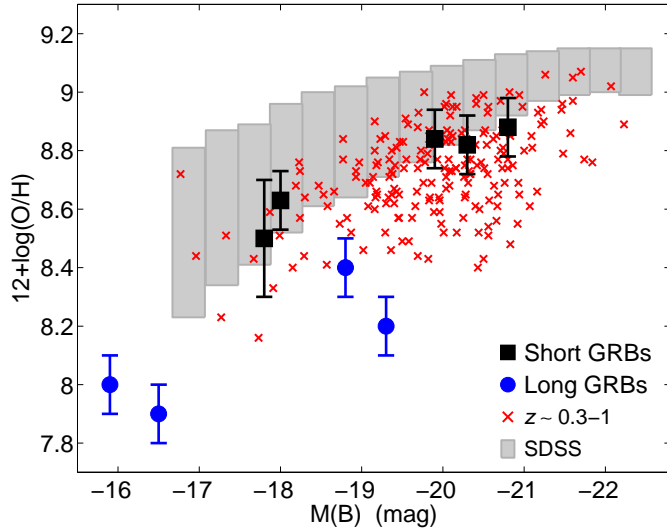


Figure 8: Metallicity as a function of B -band absolute magnitude for the host galaxies of short GRBs (black squares) and long GRBs (blue circles). The gray bars mark the 14 – 86 percentile range for galaxies at $z \sim 0.1$ from the Sloan Digital Sky Survey (Tremonti et al., 2004), while red crosses designate the same field galaxies at $z \sim 0.3 - 1$ shown in Figure 7 (Kobulnicky and Kewley, 2004). Both field samples exhibit a clear luminosity-metallicity relation. The long GRB hosts tend to exhibit lower than expected metallicities (Stanek et al., 2006), while the hosts of short GRBs have higher metallicities by about 0.6 dex, are moreover in excellent agreement with the luminosity-metallicity relation. From Berger (2009).

the same underlying distribution is 0.1. On the other hand, a comparison to the GOODS-N sample reveals a similar distribution, and the K-S probability that the short GRB hosts are drawn from the field sample is 0.6 (Berger, 2009).

A similar conclusion is reached based on a comparison of specific star formation rates (Berger, 2009). For long GRB hosts the inferred star formation rates range from about 0.2 to $50 \text{ M}_{\odot} \text{ yr}^{-1}$, and their specific star formation rates are about $3 - 40 \text{ M}_{\odot} \text{ yr}^{-1} L_{*}^{-1}$, with a median value of about $10 \text{ M}_{\odot} \text{ yr}^{-1} L_{*}^{-1}$ (Christensen et al., 2004). As shown in Figure 7, the specific star formation rates of short GRB hosts are systematically below those of long GRB hosts, with a median value that is nearly an order of magnitude lower. Indeed, the K-S probability that the short and long GRB hosts are drawn from the same underlying distribution is only 0.003 (Berger, 2009). This is clearly seen from the cumulative distributions of specific star formation rates for each sample (inset of Figure 7). On the other hand, a comparison to the specific star formation rates of the GOODS-N field galaxies reveals excellent agreement (Figure 7). The K-S probability that the short GRB hosts are drawn from the field galaxy distribution is 0.6. Thus, short GRB hosts appear to be drawn from the normal population of star forming galaxies at $z \lesssim 1$, in contrast to long GRB hosts, which have elevated specific star formation rates, likely as a result of preferentially young starburst populations (Christensen et al., 2004; Savaglio et al., 2008).

Finally, the metallicities measured for short GRB hosts are in excellent agreement with the luminosity-metallicity relation for field galaxies at $z \sim 0.1 - 1$ (Figure 8; (Kobulnicky and Kewley,

2004; Tremonti et al., 2004)). The two hosts with $M_B \approx -18$ mag have $12 + \log(\text{O}/\text{H}) \approx 8.6$, while those with $M_B \approx -20$ to -21 mag have $12 + \log(\text{O}/\text{H}) \approx 8.8 - 8.9$, following the general trend. On the other hand, the short GRB host metallicities are systematically higher than those of long GRB hosts, which have been argued to have lower than expected values (Stanek et al., 2006). The median metallicity of short GRB hosts is about 0.6 dex higher than for long GRB hosts, and there is essentially no overlap between the two host populations (Berger, 2009).

To conclude, the short GRB host sample is dominated by star forming galaxies, but these galaxies have higher luminosities, lower star formation rates and specific star formation rates, and higher metallicities than the star forming host galaxies of long GRBs. Instead, the short GRB host sample appears to be drawn from the field galaxy population. These results suggest that while short GRB hosts are mainly star forming galaxies, the progenitors most likely trace stellar mass rather than the modest on-going star formation activity.

4. Host Galaxy Stellar Masses and Ages

To more comprehensively address whether short GRBs trace stellar mass alone (as would be expected for an old progenitor population), it is essential to determine the stellar masses and population ages of short GRB host galaxies, primarily in comparison to the general galaxy stellar mass function. This analysis was recently carried out by Leibler and Berger (2010) using multi-band optical and near-IR data for 19 short GRB hosts. The resulting spectral energy distributions were fit with the Maraston (2005) stellar population models to extract two crucial parameters: stellar mass (M_{*}) and population age (τ). The range of possible masses was assessed using three approaches. First, using single stellar population (SSP) fits, which provide an adequate representation for the early-type hosts, but tend to under-estimate the total mass and population age of star-forming hosts. At the other extreme, the near-IR data alone were modeled with a stellar population matched to the age of the universe at each host redshift. This approach uses the maximum possible mass-to-light ratio to extract a maximal mass for each host galaxy. Finally, as a more realistic estimate for the star-forming hosts, hybrid young+old stellar populations were used. Examples of all three approaches are shown for the host of GRB 050709 in Figure 9.

The resulting mass distributions are shown in Figure 10. For comparison I also present the mass distributions for long GRB hosts, which were analyzed with the same models for the purpose of a uniform comparison. The SSP masses span three orders of magnitude, $M_{\text{SSP}} \approx 6 \times 10^8 - 4 \times 10^{11} \text{ M}_{\odot}$, with a median value of $\langle M_{\text{SSP}} \rangle \approx 1.3 \times 10^{10} \text{ M}_{\odot}$. Dividing the sample into early- and late-type host galaxies, the former span the range $M_{\text{SSP}} \approx (2 - 40) \times 10^{10} \text{ M}_{\odot}$, while the latter have much lower masses of $M_{\text{SSP}} \approx (0.06 - 2) \times 10^{10} \text{ M}_{\odot}$. The clear distinction between the two samples partially reflects the bias of single age SSP models, which for the late-type hosts are dominated by the young stellar population and hence under-estimate the contribution of any older stellar populations. For the maximal masses the range is $M_{\text{Max}} \approx 6 \times 10^9 - 8 \times 10^{11} \text{ M}_{\odot}$. The

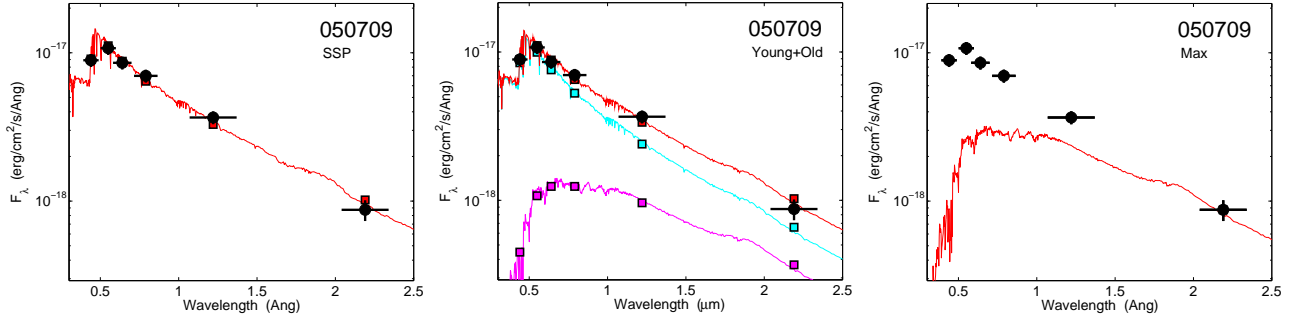


Figure 9: Optical and near-IR spectral energy distribution of GRB 050709 with the three models used to extract the stellar mass and population age. Data are shown as black circles with error bars, and synthesized model fluxes are shown as red squares. *Left*: Single age SSP model. *Center*: Young+Old SSP model (magenta=old; cyan=young) with the old population age fixed at the age of the universe at the redshift of the burst ($z = 0.161$ in this case). *Right*: Maximal mass model with the population age fixed at the age of the universe and using only the K -band photometry. The Young+Old model leads to total masses intermediate between the single age SSP and the maximal models, and has younger ages for the young population than the single age SSP model. From Leibler and Berger (2010).

median mass is $\langle M_{\text{Max}} \rangle \approx 1 \times 10^{11} M_{\odot}$, about an order of magnitude larger than for the single age SSP masses, and only slightly larger than the stellar mass of the Milky Way. As expected, the ratios of maximal to SSP masses for the early-type hosts are modest, $M_{\text{Max}}/M_{\text{SSP}} \approx 2 - 8$, since these hosts are already dominated by old stellar populations. However, for the late-type hosts the corrections are significant, $M_{\text{Max}}/M_{\text{SSP}} \approx 5 - 60$, with a median ratio of about an order of magnitude. Finally, using the young+old models for the late-type hosts, and the single age SSP values for the early-type hosts, the resulting masses are $M \approx 2 \times 10^9 - 4 \times 10^{11} M_{\odot}$, with a median of $\langle M \rangle \approx 5 \times 10^{10} M_{\odot}$.

Stellar population ages can only be inferred for the single age SSP models since for the maximal and young+old models the inherent assumption is a population with the age of the universe at each host redshift. The distribution of ages is shown in Figure 11, with the values ranging from about 30 Myr to 4.4 Gyr. The median age is $\langle \tau_{\text{SSP}} \rangle \approx 0.3$ Gyr for the full sample, with $\langle \tau_{\text{SSP}} \rangle \approx 0.25$ Gyr for the subset of late-type hosts and $\langle \tau_{\text{SSP}} \rangle \approx 3$ Gyr for the subset of early-type hosts.

The long GRB hosts, on the other hand, have lower masses and younger population ages. For the SSP model the mass range is $M_{\text{SSP}} \approx 6 \times 10^6 - 2 \times 10^{10} M_{\odot}$, with a median value of $\langle M_{\text{SSP}} \rangle \approx 1.3 \times 10^9 M_{\odot}$ (Figure 10). The maximal masses span $M_{\text{Max}} \approx 9 \times 10^7 - 9 \times 10^{10} M_{\odot}$, with a median value of $\langle M_{\text{Max}} \rangle \approx 4.0 \times 10^9 M_{\odot}$ (Figure 10). The SSP stellar population ages span about 10 to 570 Myr, with a median value of $\langle \tau_{\text{SSP}} \rangle \approx 65$ Myr.

4.1. Host Demographics

In the redshift range relevant for short GRBs ($z \sim 0.2 - 1$) roughly an equal fraction of the cosmic stellar mass budget resides in early- and late-type galaxies (e.g., (Ilbert et al., 2010)). Therefore, if short GRBs track stellar mass alone we expect a roughly one-to-one ratio of galaxy types. This does not appear to be the case. For example, within the sample of short GRBs with optical afterglows (20 events), only 2 are unambiguously hosted by early-type galaxies (GRBs 050724 and 100117; (Berger et al., 2005), Fong et al. in prep.), while 8 are unambiguously hosted by late-type galaxies; the probability of

obtaining this ratio from an intrinsic one-to-one distribution is only 0.04. The identity of the remaining 9 hosts is unclear at the present due to their faintness or the lack of underlying galaxies at the burst positions. Still, unless nearly all of these bursts were hosted by early-type galaxies, the resulting ratio appears to be skewed in favor of late-type host galaxies with on-going star formation activity. The same result holds true even when considering the bursts with only X-ray afterglow positions and identified hosts.

Thus, the host galaxy demographics suggest that short GRBs do not track stellar mass alone, or phrased alternatively, they do not have a delay time distribution that is skewed to old ages of \sim few Gyr. It is possible, however, that this result is influenced by secondary factors such as the typical circumburst density or intrinsic differences in the energy scale and afterglow brightness as a function of galaxy type (possibly reminiscent of the differences in peak luminosity for Type Ia supernovae in early- and late-type galaxies; (Hamuy et al., 2000; Mannucci et al., 2006)). If such differences lead to fainter afterglows (or prompt emission) for short GRBs in early-type galaxies, this would suppress the early-type fraction. Although the modest size of the host sample, and the substantial fraction of short GRBs with only γ -ray positions ($\sim 1/3$ of all events), prevent definitive conclusions, it does not appear that the optical afterglows of short GRBs in early- and late-type galaxies are distinct (Berger, 2010); see §6.

4.2. Comparison to the Galaxy Mass Function

I next turn to a comparison of the inferred stellar masses with the galaxy mass function (Leibler and Berger, 2010). The cumulative distribution of stellar masses for the short GRB hosts is shown in Figure 12 with the range of possible masses bounded by the single age SSP and maximal values. I also present a breakdown of the sample into early- and late-type galaxies, each spanning the same range. For the late-type hosts, the intermediate young+old values are also shown. To compare these distributions to the distribution of galaxy masses I also plot the cumulative stellar mass function *weighted by mass*, i.e., the fraction of stellar mass in galaxies above some mass,

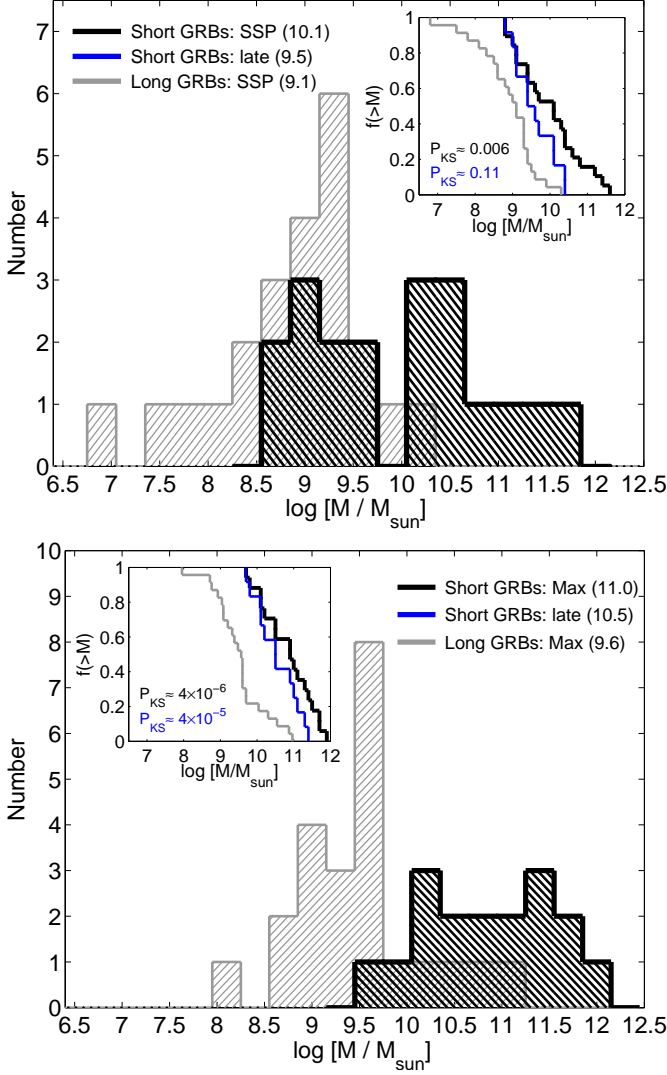


Figure 10: *Top*: Histograms of inferred stellar masses from single stellar population fits for the hosts of short (black) and long (gray) GRBs. The inset shows the cumulative distributions, including for the subset of late-type short GRB hosts (blue). The median values for the three samples are given in parentheses, and the Kolmogorov-Smirnov probabilities that the distributions of short and long GRB hosts, as well as star forming short GRB and long GRB hosts are drawn from the same distribution are provided in the inset. *Bottom*: Same but for the maximal masses. From Leibler and Berger (2010).

$f(> M)$, given by the equation:

$$f(> M) = \frac{\int_M^\infty M' \times \Phi(M') dM'}{\int_0^\infty M' \times \Phi(M') dM'} \quad (1)$$

where $\Phi(M)$ is the Schechter mass function:

$$\Phi(M) = \Phi^* \left(\frac{M}{M^*} \right)^\alpha \exp \left(- \frac{M}{M^*} \right). \quad (2)$$

Several determinations of $\Phi(M)$ are used for this comparison, including the Cole et al. (2001) mass function from the 2MASS/2dF catalogs for all galaxy types at $z \sim 0$ ($M^* = 10^{11.16} M_\odot$, $\alpha = -1.18$); the nearly identical Panter et al. (2004) mass function from SDSS for all galaxy types at $z \sim 0$ ($M^* = 10^{11.19}$

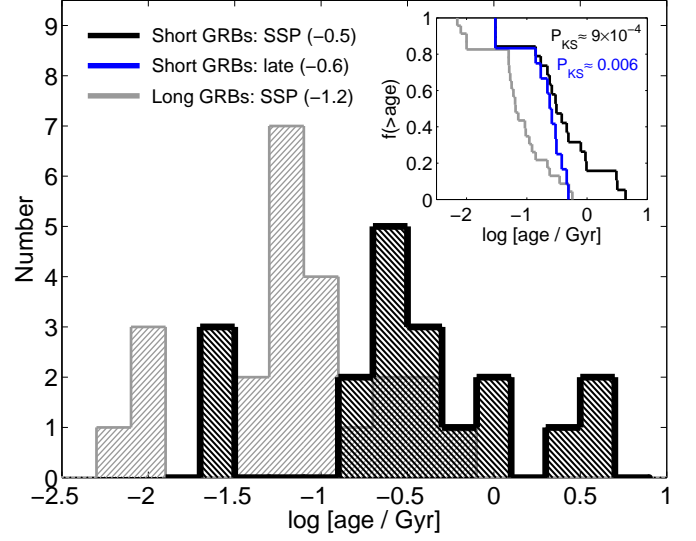


Figure 11: Histograms of inferred stellar population ages from single stellar population fits for the hosts of short (black) and long (gray) GRBs. The inset shows the cumulative distributions, including for the subset of late-type short GRB hosts (blue). The median values for the three samples are given in parentheses, and the Kolmogorov-Smirnov probabilities that the distributions of short and long GRB hosts, as well as star forming short GRB and long GRB hosts are drawn from the same distribution are provided in the inset. From Leibler and Berger (2010).

M_\odot , $\alpha = -1.16$); the Bell et al. (2003) mass function for late-type galaxies from 2MASS/SDSS converted to a Salpeter IMF for comparison with our inferred values ($M^* = 10^{10.97} M_\odot$, $\alpha = -1.27$); and the Ilbert et al. (2010) mass functions from the COSMOS survey for quiescent galaxies at $z \sim 0.3$ ($M^* = 10^{11.13} M_\odot$, $\alpha = -0.91$) and intermediate-activity galaxies at $z \sim 0.5$ ($M^* = 10^{10.93} M_\odot$, $\alpha = -1.02$), matched to the redshifts of the early- and late-type short GRB host galaxies in our sample. The resulting distributions of $f(> M)$ for the various mass functions are shown in Figure 12.

The agreement (or lack thereof) between the short GRB hosts and the galaxy mass functions is assessed using the Kolmogorov-Smirnov (K-S) test. For the full sample there is negligible probability that the distribution of single age SSP masses is drawn from the galaxy mass function, with $P \approx 8 \times 10^{-5}$. On the other hand, for the maximal mass distribution the probability is $P \approx 0.6$ indicating that for these masses the short GRB sample is fully consistent with the galaxy mass function. Using the intermediate case of SSP masses for the early-type hosts and the young+old masses for the late-type hosts, the probability is $P \approx 0.3$, indicating that this combination is also consistent with the galaxy mass function.

Separating the early-type hosts, their SSP masses are consistent with the Ilbert et al. (2010) mass function of quiescent galaxies ($P \approx 0.8$); their large maximal masses, on the other hand, are inconsistent with the mass function, with $P \approx 0.007$. Finally, for the late-type hosts there is a clear inconsistency of the single age SSP masses with the Ilbert et al. (2010) mass function of intermediate-activity galaxies, with $P \approx 4 \times 10^{-7}$. However, the maximal mass distribution is consistent with the mass function ($P \approx 0.3$), while the young+old mass distribution

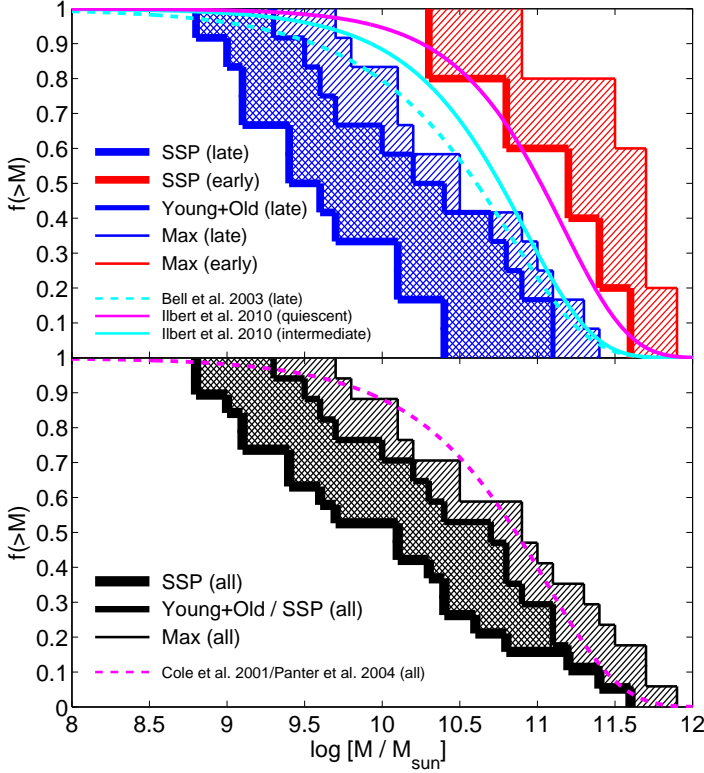


Figure 12: Cumulative distributions for the full sample of single age simple stellar population (SSP) masses, maximal masses, and combined young+old and SSP masses for the late- and early-type hosts, respectively (black; bottom panel). The upper panel shows a breakdown by galaxy type (late-type: blue; early-type: red). The shaded regions represent the range of possible stellar masses since the SSP masses, which are effectively light-weighted values, are most likely an under-estimate, while the maximal masses make the extreme assumption that all hosts are dominated by populations with the age of the universe. For the late-type hosts the total masses from a young+old SSP fit are also shown; these are more closely representative of the total mass. Also shown are the fractions of total stellar mass in galaxies with mass, $> M$, calculated from several published galaxy stellar mass functions at $z \sim 0-2$ (cyan and magenta lines; (Cole et al., 2001; Bell et al., 2003; Panter et al., 2004; Ilbert et al., 2010)); for the Ilbert et al. (2010) mass function the $z \sim 0.5$ bin is used, appropriate for the short GRB sample, and separately plot the mass function for quiescent galaxies and for intermediate-activity galaxies, which resemble the intermediate star formation activity in short GRB hosts (Berger, 2009). The comparison indicates that short GRBs trace galaxy mass *only* if the bulk of the late-type hosts have close to maximal masses. The subset of early-type hosts appears to faithfully trace the mass function of galaxies for the SSP-derived masses. From Leibler and Berger (2010).

is marginally consistent ($P \approx 0.1$).

To summarize, the distribution of short GRB host masses is compatible with the overall mass distribution of galaxies only if their stellar masses are given by the SSP masses for the early-type hosts and the maximal or young+old masses for the late-type hosts. Since the opposite scenario (maximal masses for the early-type hosts and SSP masses for the late-type hosts) is unlikely, the existing sample of short GRB hosts is consistent with the galaxy mass function (Leibler and Berger, 2010). Equivalently, this means that short GRBs may indeed track stellar mass alone. However, I caution that the host demographics seem to be at odds with the expected equal fractions of total stellar mass in early- and late-type galaxies, unless nearly all

of the unidentified hosts are early-type galaxies. This, along with the somewhat lower than expected masses of the late-type hosts, leaves open the possibility that at least a subset of short GRB progenitors track star formation activity rather than stellar mass.

4.3. Comparison to Long GRB Hosts

Despite the possibility that some short GRB progenitors may track star formation activity, the inferred stellar masses and population ages of short GRB hosts are generally distinct from those of long GRB hosts in both the single age SSP and maximal models (Leibler and Berger, 2010). Most importantly, this is true for the subset of late-type hosts. In the framework of the single age SSP model the K-S probability is only 0.006 that the long and short GRB hosts are drawn from the same mass distribution. The probability is higher for the subset of late-type short GRB hosts, $P \approx 0.1$ (Figure 10). However, since the SSP values represent the mass of only the young stellar populations, they are mostly reflective of the star formation activity rather than the total stellar mass. Using instead the maximal masses, the K-S probability that the long GRB hosts and late-type hosts of short GRBs are drawn from the same sample is negligible, $P \approx 4 \times 10^{-5}$ (Figure 10), demonstrating that they are distinct galaxy populations. A similar conclusion is apparent from a comparison of the single age SSP population ages. The K-S probability that the long GRB hosts and late-type hosts of short GRBs are drawn from the same distribution is only $P \approx 0.006$.

Thus, the long GRB hosts have significantly lower stellar masses than the subset of late-type short GRB hosts, and their young stellar population are significantly younger. Indeed, a comparison of the long GRB host maximal masses to the Ilbert et al. (2010) mass function of high-activity galaxies at $z \sim 0.7$ (appropriate for the long GRB sample considered here) indicates a K-S probability of only 0.002 that the long GRB hosts are drawn from the galaxy mass function. This is consistent with our understanding that their massive star progenitors select galaxies by star formation (and perhaps additional factors such as metallicity), but not by stellar mass.

The apparent distinction between long GRB hosts and the late-type hosts of short GRBs in terms of their stellar masses and young population ages strengthens the conclusion in §3 based on the star formation rates, specific star formation rates, luminosities, and metallicities (Berger, 2009). In essentially every property the late-type short GRB hosts point to a population of more quiescent, massive, and evolved galaxies than the hosts of long GRBs. I therefore conclude that this rules out the idea that short GRB progenitors in late-type hosts are massive stars identical to long GRB progenitors (Virgili et al., 2009), *even if the short GRBs in late-type galaxies indeed track star formation rather than stellar mass*.

4.4. The Delay Time Distribution

A determination of the delay function from the derived stellar population ages is complicated by two primary factors. First, they rely on the assumption that the short GRB progenitors in each host were formed within the inferred stellar population.

This assumption is justified statistically both for an association of the progenitors with stellar mass and with star formation activity, as long as we can appropriately normalize the rates of short GRBs. Second, while it is possible to determine single age SSP ages from the broad-band photometry, these data are not sufficient to provide an age breakdown (by mass) for multiple stellar components. Indeed, for the hybrid young+old model, the age of the old population has to be fixed (to the age of the universe in the analysis of Leibler and Berger (2010)). Still, in the young+old model, the bulk of the mass ($\approx 55 - 99\%$) is contained in the old stellar population, and so the progenitors would have “old” ages ($\tau \gtrsim \tau_{\text{SSP}}$) if they tracked stellar mass.

As a result of these limitations it is only possible to explore the implications of two main scenarios, namely that short GRBs track mass and/or star formation activity. In the context of the former scenario I have shown in §4.2 that the short GRBs in early-type hosts trace stellar mass. Therefore, their SSP ages can be used to provide a rough estimate of the progenitor ages, $\tau \approx 0.8 - 4.4$ Gyr, with a median of about 3 Gyr. On the other hand, for the late-type hosts (for which no credible information on the mass-weighted stellar population age can be extracted), it is possible to infer a typical delay relative to the most recent star formation episode under the assumption that these progenitors track star formation activity. I find SSP ages of $\tau \approx 0.03 - 0.5$ Gyr, with a median of about 0.25 Gyr, or young+old ages of about 0.01 – 0.4 Gyr with a median of about 0.1 Gyr.

Thus, if short GRBs follow both stellar mass (in early-type galaxies) and star formation activity (in late-type galaxies), the typical delay times are about 3 and 0.2 Gyr, respectively.

5. Offsets and the Sub-Galactic Environments

I next turn from a galactic-scale investigation of short GRB host environments to the sub-galactic scale. In general, the sub-galactic environments of cosmic explosions provide powerful insight into the nature of their progenitors. For example, in the case of long GRBs, the distribution of projected physical and host-normalized offsets relative to the host centers matched the expected distribution for massive stars in an exponential disk (Bloom et al., 2002). Moreover, long GRBs are spatially correlated with the brightest UV regions of their hosts (Fruchter et al., 2006). Both of these studies have relied on high angular resolution *Hubble Space Telescope* (*HST*) observations to spatially resolve the hosts and astrometrically locate the GRB positions to pixel-scale accuracy. As a by-product, these observations also provided detailed morphological information for the hosts (e.g., Sérsic index, effective radius; e.g. (Wainwright et al., 2007)).

Individual offsets have been measured for several short GRBs (e.g., (Berger et al., 2005; Fox et al., 2005; Bloom et al., 2006)), and a study relying on ground based data without a complete astrometric treatment was published by Troja et al. (2008). However, the first systematic study of short GRB offsets, as well as their galactic environments and host morphologies was recently published by Fong et al. (2010). The sample includes ten short GRBs (spanning May 2005 to December 2006), of which seven have been localized to sub-arcsecond

precision, and of those, six are robustly associated with host galaxies (for details see (Fong et al., 2010)). Illustrative examples of *HST* host images and morphological model fits are shown in Figure 13.

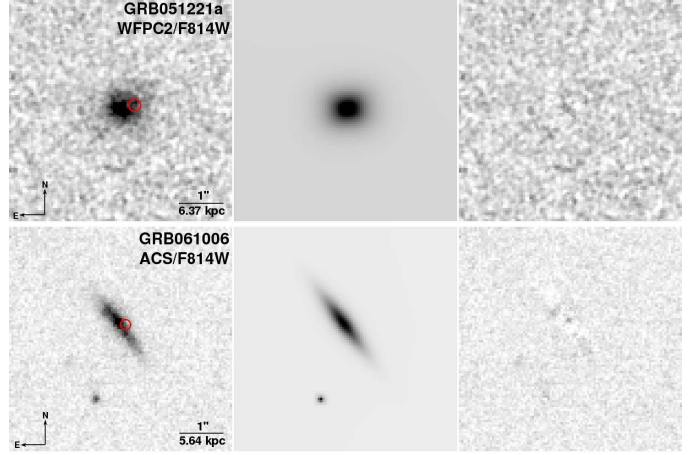


Figure 13: *Top-left*: *HST*/WFPC2/F814W image of the host galaxy of GRB 051221A with a 5σ error circle representing the afterglow position. *Top-center*: Sérsic model fit from *galfit*. *Top-right*: Residual image. *Bottom*: Same, but for the host galaxy of GRB 061006. From Fong et al. (2010).

5.1. Morphological Analysis

The two-dimensional surface brightness profiles were used to determine the hosts’ effective radii and morphological properties such as the Sérsic n index. These quantities are crucial for a comparison of the morphologies and sizes to those of long GRBs, as well as for normalization of the projected offsets relative to the galaxy size. Three hosts (GRBs 050709, 051221A, and 061006) are best modeled with $n \approx 1$, corresponding to an exponential disk profile, while two hosts (GRBs 050509B and 050724) are best modeled with $n \approx 3$ and ≈ 5.6 , respectively, typical of elliptical galaxies. These classifications are in perfect agreement with their spectroscopic properties. The final three hosts in the sample (GRBs 051210, 060121, and 060313) are faint, and as a results can be modeled with a wide range of n values, although $n \sim 1$ is preferred in all three cases. Therefore, of the eight short GRB hosts only two can be robustly classified as elliptical galaxies based on their morphology. A similar fraction was determined independently from spectroscopic observations (§3; (Berger, 2009)).

The morphological analysis also yields values of the galaxy effective radii, r_e . A range of $\approx 0.2 - 5.8''$ is found, corresponding to physical scales² of about 1.4 – 21 kpc. The smallest effective radius is measured for the host of GRB 060313, while the elliptical host of GRB 050509B has the largest effective radius. The median value for the sample is $r_e \approx 3.5$ kpc. The effective radii as a function of n are shown in Figure 15. Also

²For the faint hosts without a known redshift (GRBs 051210, 060121, 060313, and possibly 061201) it is assumed that $z = 1$ (Berger et al., 2007), and take advantage of the relative flatness of the angular diameter distance as a function of redshift beyond $z \sim 0.5$.

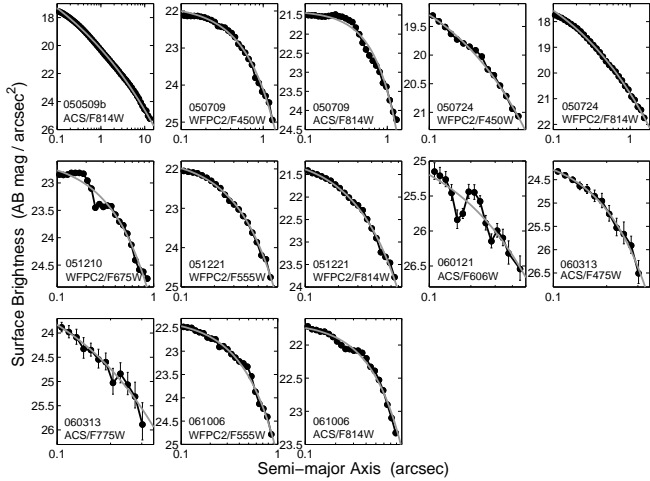


Figure 14: One-dimensional radial surface brightness profiles for short GRB host galaxies derived using the IRAF task `ellipse`. The gray lines are Sérsic model fits to the surface brightness profiles. From Fong et al. (2010).

shown are the r_e and n values for the hosts of long GRBs from a similar analysis carried out by Wainwright et al. (2007).

Two clear trends emerge from the morphological comparison of short and long GRB hosts. First, all long GRB hosts have $n \lesssim 2.5$, and the median value for the population is $\langle n \rangle \approx 1.1$ (Wainwright et al., 2007). Thus, they are all morphologically classified as exponential disk galaxies, while 2 of the 8 short GRB hosts exhibit de Vaucouleurs elliptical galaxy profiles. However, for the short GRB hosts with $n \lesssim 2$, the distribution of n values appears to be similar to that of long GRB hosts (Fong et al., 2010).

Second, the short GRB host galaxies have larger effective radii, with $\langle r_e \rangle \approx 3.5$ kpc, compared to $\langle r_e \rangle \approx 1.7$ kpc for long GRB hosts (Wainwright et al., 2007). A Kolmogorov-Smirnov (K-S) test indicates that the probability that the short and long GRB hosts are drawn from the same underlying distribution of host galaxy effective radii is only 0.04. Thus, short GRB host galaxies are systematically larger than long GRB hosts. The larger sizes are expected in the context of the well-known galaxy size-luminosity relation (e.g., (Freeman, 1970)) and the higher luminosity of short GRB hosts (§3; (Berger, 2009)).

An additional striking difference between the hosts of long and short GRBs is the apparent dearth of interacting or irregular galaxies in the short GRB sample. Of the eight short GRB host galaxies with *HST* observations only one exhibits an irregular morphology (GRB 050709) and none appear to be undergoing mergers. In contrast, the fraction of long GRB hosts with an irregular or merger/interaction morphology is ~ 30 – 60% (Wainwright et al., 2007). The interpretation for the high merger/interaction fraction in the long GRB sample is that such galaxies represent sites of intense star formation activity triggered by the merger/interaction process, and are therefore suitable for the production of massive stars (Wainwright et al., 2007). The lack of morphological merger signatures in the short GRB sample indicates that if any of the hosts have undergone significant mergers in the past, the delay time between

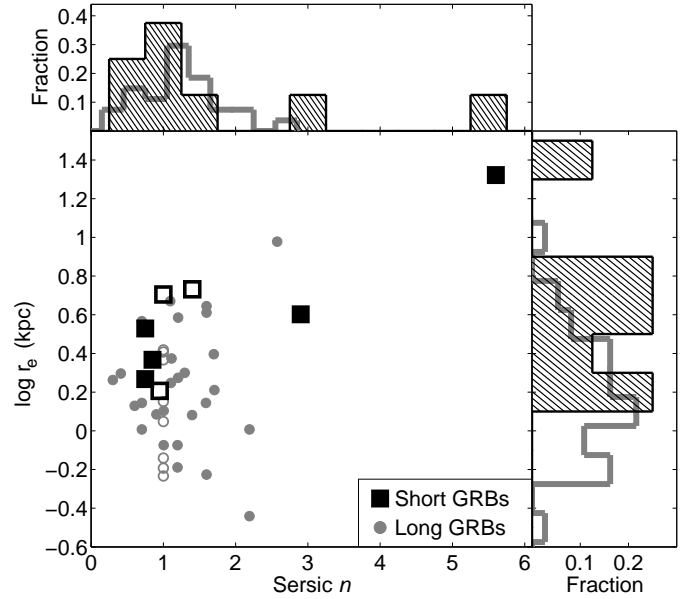


Figure 15: Effective radii for the short GRB hosts observed with *HST* as a function of their Sérsic n values (Figure 14). Also shown are the data for long GRB hosts based on *HST* observations from the sample of Wainwright et al. (2007). The hosts of short GRBs 050509B and 050724 have n values typical of elliptical galaxies, but the remaining hosts have a similar distribution to that of long GRBs (i.e., a median of $n \sim 1$, or an exponential disk profile). On the other hand, the hosts of short GRBs are larger by about a factor of 2 than the hosts of long GRBs, in agreement with their higher luminosities. From Fong et al. (2010).

the merger and the occurrence of a short GRB is $\gtrsim 1$ Gyr (e.g., (Barnes and Hernquist, 1992)).

5.2. The Offset Distribution

The location of each short GRB relative to its host galaxy center and its overall light distribution was determined through differential astrometry using optical and near-IR images of the afterglows³ (Fong et al., 2010). With the exception of GRB 050709, whose afterglow is directly detected in *HST* observations, ground-based afterglow images from Magellan, Gemini, and the VLT were used. The resulting positional uncertainties include contributions from the ground-based to *HST* astrometric tie ($\sigma_{\text{GB} \rightarrow \text{HST}} \approx 10 - 30$ mas), the positional uncertainty of the afterglow ($\sigma_{\theta, \text{GRB}} \approx 1 - 40$ mas for optical afterglows and $\approx 1.7 - 5.8$ arcsec for X-ray afterglows), and the uncertainty in the centroid of the host galaxy ($\sigma_{\theta, \text{gal}} \approx 1 - 20$ mas). The resulting combined offset uncertainties for the short GRBs with optical afterglows are $\lesssim 60$ mas, corresponding to physical offset uncertainties of $\lesssim 0.5$ kpc; the best-measured offsets have uncertainties at the level of tens of pc. These offsets also correspond to about 1 *HST* pixel.

Based on the resulting astrometric ties Fong et al. (2010) find that the projected offsets of short GRBs relative to their host centers range from about 0.12 to $17.7''$. The corresponding projected physical offsets are about $1 - 64$ kpc, with a median

³Optical afterglows have not been detected for GRBs 050509B and 051210.

value of about 5 kpc. The largest offsets are measured for GRBs 050509B and 051210, but those are based on *Swift*/XRT positions only, with statistical uncertainties of 12 and 18 kpc, respectively. considering only the bursts with sub-arcsecond afterglow positions, the largest offset is 3.7 kpc (GRB 050709), and the median offset for the 6 bursts is 2.2 kpc. In the case of GRB 061201 the host association remains ambiguous, but even for the nearest detected galaxy the offset is about 14.2 kpc.

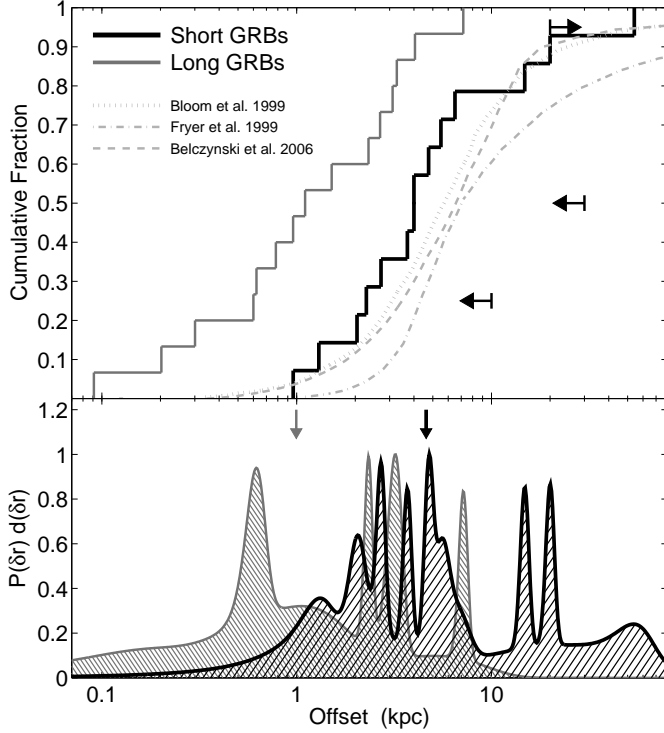


Figure 16: Projected physical offsets for short GRBs (black) and long GRBs (gray; (Bloom et al., 2002)). The top panel shows a cumulative distribution, while the bottom panel shows the differential distribution taking into account the non-Gaussian errors on the offsets. The arrows in the bottom panel mark the median value for each distribution. The median value for short GRBs, ≈ 5 kpc, is about a factor of 5 times larger than for long GRBs. The arrows in the top panel mark the most robust constraints on the offset distribution, taking into account the fraction of short GRBs with only γ -ray positions, as well as short GRBs for which hosts have been identified within XRT error circles (thereby providing a typical range of $\sim 0-30$ kpc). Also shown in the top panel are predicted offset distributions for NS-NS binary mergers in Milky Way type galaxies based on population synthesis models. Good agreement between the observed distribution and models, as well as between the robust constraints and models is found. From Fong et al. (2010).

To investigate the offset distribution in greater detail the *HST* sample was supplemented with offsets for GRBs 070724, 071227, 080905A, and 090510 from ground-based observations (Berger et al., 2009; Rau et al., 2009; Rowlinson et al., 2010). These bursts have accurate positions from optical afterglow detections. In the case of GRBs 070724 and 071227 the optical afterglows coincide with the disks of edge-on spiral galaxies (Figure 2; (Berger et al., 2009; D’Avanzo et al., 2009)). The offsets of the three bursts are 4.8, 14.8, 18.5, and 5.5 kpc, respectively.

There are 7 additional events with optical afterglow identifications. Of these, two bursts (070707 and 070714B) coincide

with galaxies (Piranomonte et al., 2008; Graham et al., 2009), but their offsets have not been reported by the authors. Based on the claimed coincidence a conservative estimate is $\lesssim 0.5''$, corresponding⁴ to $\lesssim 4$ kpc. For GRB 090426 an offset relative to one of the knots in the host galaxy complex was reported (Levesque et al., 2010), but not relative to the host center. Finally, four bursts (070809, 080503, 090305, 090515) do not have coincident host galaxies to deep limits; these bursts are discussed in detail in §6.

In addition to the bursts with sub-arcsecond positions, several hosts have been identified within XRT error circles in follow-up observations (GRBs 060801, 061210, 061217, 070429B, 070729, and 080123; (Berger et al., 2007; Berger, 2009)). Since the putative hosts are located within the error circles, the offsets are consistent with zero or may be as large as ~ 30 kpc (e.g., (Berger et al., 2007)). For example, the offsets for GRBs 060801, 061210, and 070429B are 19 ± 16 kpc, 11 ± 10 kpc, and 40 ± 48 kpc. I adopt 30 kpc as a typical upper limit on the offset for these 6 events. No follow-up observations are available in the literature for most short GRBs with X-ray positions from 2008-2010. Finally, about $1/4 - 1/3$ of all short GRBs discovered to date have only been detected in γ -rays with positional accuracies of a few arcminutes, thereby precluding a unique host galaxy association and an offset measurement.

The cumulative distribution of projected physical offsets for the GRBs with *HST* observations (Fong et al., 2010), supplemented by the bursts with offsets or limits based on optical afterglow positions (070707, 070714B, 070724, 070809, 071227, 080503, and 090510) is shown in Figure 16. Also shown is the differential probability distribution, $P(\delta r)d(\delta r)$, taking into account the non-Gaussian errors on the radial offsets (see discussion in Appendix B of (Bloom et al., 2002)). The median for this sample is about 5 kpc (Fong et al., 2010).

As evident from the preceding discussion, this is not a complete offset distribution; roughly an equal number of short GRBs have only limits or undetermined offsets due to their detection in just the X-rays or γ -rays⁵. Taking these events into account, our most robust inferences about the offset distribution of short GRBs are as follows:

- At least 25% of all short GRBs have projected physical offsets of $\lesssim 10$ kpc.
- At least 5% of all short GRBs have projected physical offsets of $\gtrsim 20$ kpc.
- At least 50% of all short GRBs have projected physical offsets of $\lesssim 30$ kpc; this value includes the upper limits for the hosts identified within XRT error circles.

These robust constraints are marked in Figure 16.

⁴GRB 070714B is located at $z = 0.923$, while the redshift of GRB 070707 is not known. Based on the faintness of the host, $R \approx 27.3$ mag, we assume $z = 1$ to calculate the physical offset.

⁵I do not consider the bursts that lack host searches since there is no a priori reason that these events (mainly from 2008-2010) should have a different offset distribution compared to the existing sample.

I next compare the short GRB offset distribution with the offsets of long GRBs from the sample of Bloom et al. (2002); see Figure 16. The offset distribution of long GRBs has been used to argue for a massive star progenitor population, and against NS-NS binaries (Bloom et al., 2002). The offset distribution of short GRBs is clearly shifted to larger physical scales. In particular, the median offset for the long GRBs is 1.1 kpc, about a factor of 5 times smaller than the median value for short GRBs. Similarly, no long GRB offsets are larger than about 7 kpc, whereas at least some short GRBs appear to have offsets in excess of 15 kpc. The significant difference between the offset distributions indicates that short GRBs do not arise from the same progenitor population as long GRBs.

I further compare the observed distribution (and the robust constraints outlined above) with predicted distributions for NS-NS binaries in Milky Way type galaxies (Bloom et al., 1999; Fryer et al., 1999; Belczynski et al., 2006), appropriate for the observed luminosities of short GRB host galaxies (Berger, 2009). There is good agreement between the observed distribution and those predicted by Bloom et al. (1999) and Belczynski et al. (2006). The offset distribution of Fryer et al. (1999), with a median of about 7 kpc, predicts larger offsets and therefore provides a poorer fit to the observed distribution, which has a median of about 5 kpc. However, all three predicted distributions accommodate the offset constraints. In particular, they predict about 60–75% of the offsets to be $\lesssim 10$ kpc, about 80–90% to be $\lesssim 30$ kpc, and about 10–25% of the offsets to be $\gtrsim 20$ kpc. Thus, the projected physical offsets of short GRBs are consistent with population synthesis predictions for NS-NS binaries. However, the observations are also consistent with partial contribution from other progenitor systems for which kicks are not expected (magnetars, WD-WD binaries, accreting NS).

5.3. Light Distribution Analysis

In addition to the offset analysis in the previous section, Fong et al. (2010) studied the local environments of short GRBs using a comparison of the host brightness at the GRB location to the overall host light distribution. This approach is advantageous because it is independent of galaxy morphology, and does not suffer from ambiguity in the definition of the host center (see (Fruchter et al., 2006)). I note that for the regular morphologies of most short GRB hosts (§5.1), the definition of the host center is generally robust, unlike in the case of long GRBs (Fruchter et al., 2006; Wainwright et al., 2007). On the other hand, this approach has the downside that it requires precise pixel-scale positional accuracy. In the existing sample, this is only available for 6 short bursts.

The fraction of total host light in pixels fainter than the afterglow pixel brightness for each host/filter combination is given in Fong et al. (2010). The cumulative light distribution histogram is shown in Figure 17. The shaded histogram represents the range defined by the dual filters for 5 of the 6 bursts. The upper bound of the distribution is defined by the blue filters, indicating that short GRBs trace the rest-frame optical light of their hosts better than the rest-frame UV. This indicates that

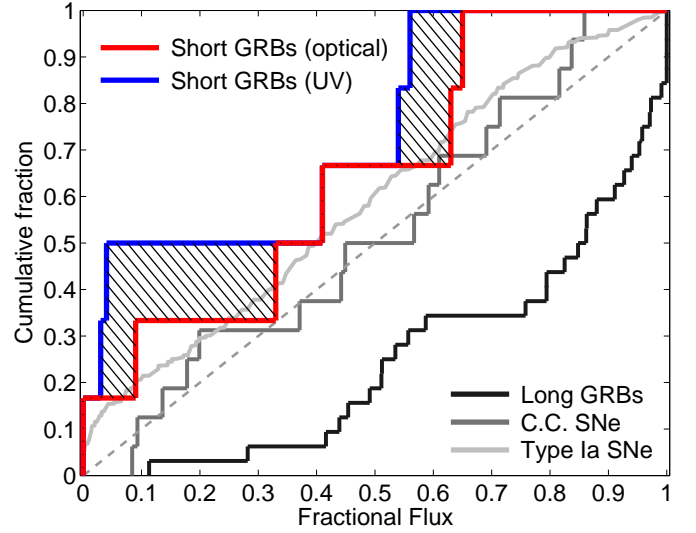


Figure 17: Cumulative distribution of fractional flux at the location of short GRBs relative to their host light. For each burst the fraction of host light in pixels fainter than the GRB pixel location is measured. The shaded area is defined by the results for the two available filters for each short GRB. Also shown are data for long GRBs (dark gray line) and for core-collapse and Type Ia SNe (light gray lines) from Fruchter et al. (2006) and Kelly et al. (2008). The dashed line marks the expected distribution for objects which track their host light distribution. Short GRBs appear to under-represent their host light, while long GRBs tend to be concentrated in the brightest regions of their hosts (Fruchter et al., 2006). From Fong et al. (2010).

short GRB progenitors are likely to be associated with a relatively old stellar population, rather than a young and UV bright population.

The overall distribution has a median value of $\approx 0.1 - 0.4$ (blue vs. red filters); namely, only in about one-quarter of the cases, 50% of the host light is in pixels fainter than at the GRB location. Thus, the overall distribution of short GRB locations under-represents the host galaxies light distribution, but traces the red light (old stars) more closely than the blue light (star formation). This is also true in comparison to the distribution for core-collapse SNe, which appear to track their host light (Fruchter et al., 2006), and even Type Ia SNe, which have a median of about 0.4 (Kelly et al., 2008). Thus, the progenitors of short GRBs appear to be more diffusely distributed than Type Ia SN progenitors.

An extensive analysis of the brightness distribution at the location of long GRBs has been carried out by Fruchter et al. (2006). These authors find that long GRBs are more concentrated on the brightest regions of their hosts than expected from the light distribution of each host. In particular, they conclude that the probability distribution of long GRB positions is roughly proportional to the surface brightness squared. As can be seen from Figure 17, short GRBs have a significantly more diffuse distribution relative to the host light than long GRBs. In particular, for the latter, the median light fraction is about 0.85 compared to about 0.25 ± 0.15 for the short GRBs.

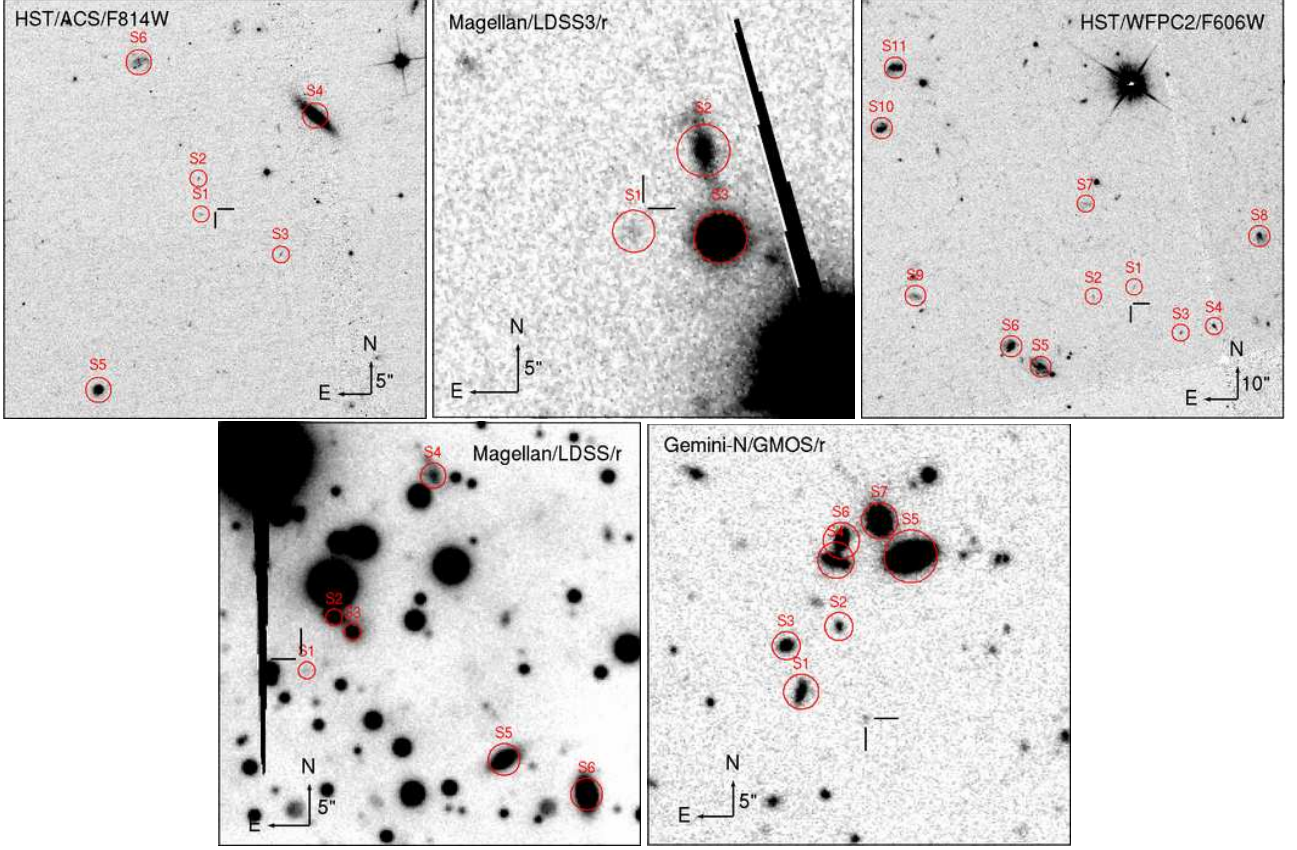


Figure 18: Images of the fields around the optical afterglow positions of short GRBs 061201, 070809, 080503, 090305A, and 090515 (top-left to bottom-right). These are the 5 bursts in the current sample that have optical afterglow positions and no coincident hosts to limits of $\gtrsim 25.5$ mag. From Berger (2010).

6. Is There Evidence for Large Progenitor Kicks?

One of the predictions of the compact object coalescence model is that some binaries could merge at large separations from their host galaxies due to a combination of large kick velocities and a long merger timescale (Bloom et al., 1999; Fryer et al., 1999; Belczynski et al., 2006). With kicks of several hundred km s^{-1} and merger timescales of $\sim \text{Gyr}$, such a binary could travel several hundred kpc from its host, corresponding to $\sim 1'$ at $z \sim 1$ and $\sim 10'$ at $z \sim 0.1$. Such large offsets would not be expected in other progenitor scenarios. It is important to note, however, that if the typical kick velocities are $\lesssim 10^2 \text{ km s}^{-1}$, an NS-NS/NS-BH system is likely to remain bound to its host regardless of the merger timescale, and hence to reside at offsets of \lesssim tens of kpc (as already inferred for some short GRBs (Fong et al., 2010); Figure 16). Similarly, short merger timescales (tens to hundreds of Myr) would also lead to relatively small offsets regardless of the kick velocity.

Clearly, an observational demonstration of a large offset is not trivial. Ideally, we would like to measure the redshift of the burst directly through afterglow spectroscopy and then associate it with a galaxy at a large separation. However, to date, short GRB redshifts have been measured through their host associations so this test is not possible.

At a more tentative level, we can also investigate the large-scale environments around short GRBs that do not appear to

spatially coincide with bright galaxy counterparts to assess the potential for a host with large offset. This is a particularly important test if combined with the afterglow properties of short GRBs with and without coincident hosts. In the current sample, there are 5 cases of short GRBs with sub-arcsecond positions and no obvious bright hosts⁶. Below, I assess the possibility of large offsets for these bursts, and compare this with alternative explanations (e.g., a high redshift origin). The sample includes 20 short GRBs with optical afterglows. Images of the fields around the 5 bursts with no coincident hosts are shown in Figure 18; hereafter, I denote these 5 bursts as *Sample 2*, with the remaining 15 bursts with coincident hosts designated as *Sample 1*. The afterglow positions, as well as nearby galaxies with varying probabilities of chance coincidence are marked in Figure 18. The limits at the positions of the afterglows range from $\gtrsim 25.5$ to $\gtrsim 26.5$ mag (Berger, 2010).

In terms of the afterglow properties, the bursts in *Sample 2* have a median optical brightness that is 1.4 mag fainter than the bursts in *Sample 1* (Figure 19, and X-ray fluxes at 8 hours that are about a factor of 2 times smaller. Their γ -ray fluences are similarly smaller, by about a factor of 5 (Berger, 2010). The differences in optical afterglow brightness can be due to lower

⁶I do not discuss cases with only XRT positions of a few arcsec radius since those do not generally lead to significant offsets and furthermore nearly always contain at least one possible host consistent with zero offset.

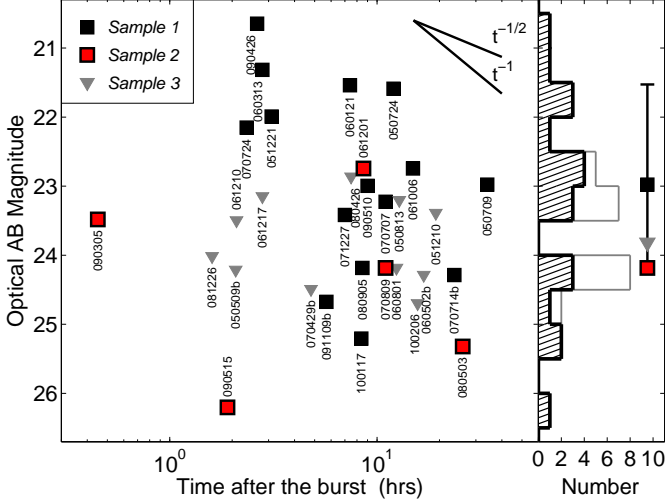


Figure 19: Optical afterglow brightness on timescales of a few hours after the burst for short GRBs with detected afterglows (*Sample 1*: black squares; *Sample 2*: red squares) or upper limits (gray triangles). The lines at the top right indicate the fading tracks for afterglow decay rates of $\alpha = -0.5$ and -1 . The right panel shows the projected histogram for the bursts with detected afterglows (hatched) and upper limits (open). The symbols mark the mean for each sample, and the vertical bar marks the standard deviation for *Sample 1*. From Berger (2010).

densities or higher redshifts for *Sample 2*. Both of these scenarios would also explain the lack of bright coincident hosts, since low densities may be indicative of large offsets and high redshifts will lead to fainter host galaxies. The difference in X-ray brightness does not significantly constrain these two possibilities, while the fainter γ -ray emission of the bursts in *Sample 2* points to high redshift as the likely explanation, since in the context of the standard GRB model the prompt emission fluence does not depend on the circumburst density.

I next turn to an analysis of the large-scale environments of the bursts in *Sample 2*, particularly in comparison to the hosts of bursts in *Sample 1*. None of the 5 bursts have coincident hosts to significantly deeper limits than the hosts in *Sample 1*. I therefore investigate the possibility of large offsets through the calculation of chance coincidence probabilities for nearby galaxies, as well as the possibility of a high redshift origin. The chance coincidence probability for nearby galaxies depends on both their apparent magnitude and their distance from the optical afterglow position. The expected number density of galaxies brighter than a measured magnitude, m , is (Hogg et al., 2002; Bloom et al., 2002; Beckwith et al., 2006):

$$\sigma(\leq m) = \frac{1}{0.33 \times \ln(10)} \times 10^{0.33(m-24)-2.44} \text{ arcsec}^{-2}, \quad (3)$$

and the chance coincidence probability for a given separation, $P(< \delta R)$, is then:

$$P(< \delta R) = 1 - e^{-\pi(\delta R)^2 \sigma(\leq m)}, \quad (4)$$

where for offsets substantially larger than the galaxy size, δR is the appropriate radius in Equation 4 (Bloom et al., 2002).

The resulting distributions for each field are shown in Figure 20; I include all galaxies that have probabilities of $\lesssim 0.95$.

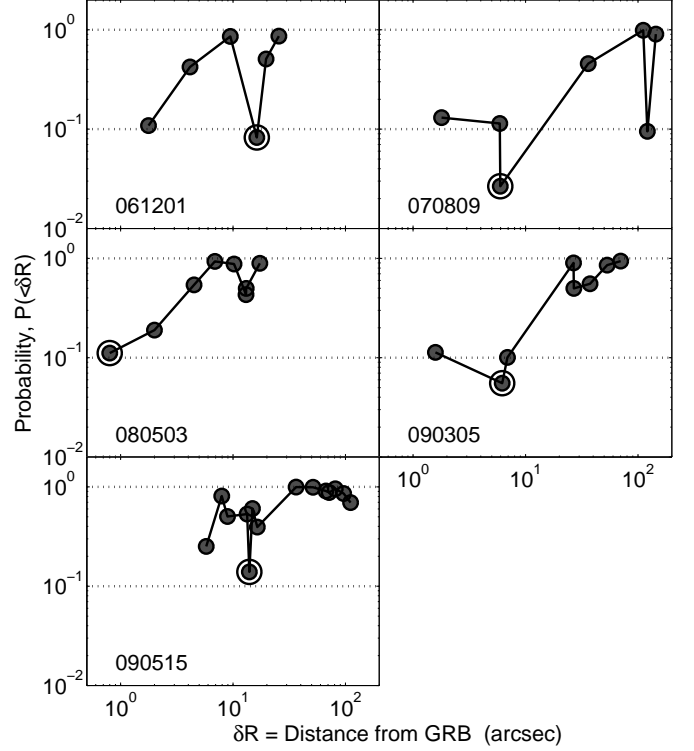


Figure 20: Probability of chance coincidence as a function of distance from a short GRB optical afterglow position for galaxies near the location of each burst. These are the galaxies marked in Figure 18. In each panel I mark the galaxy with the lowest probability of chance detection with a circle. In 4 of the 5 cases, the lowest probability is associated with galaxies that are offset by $\sim 5 - 15''$. Moreover, even the nearest galaxies are offset by $\approx 1.6 - 5.8''$. From Berger (2010).

I find that for 4 of the 5 bursts, faint galaxies ($\sim 25 - 26$ mag) can be identified within $\approx 1.6 - 2''$ of the afterglow positions, with associated chance coincidence probabilities of $\approx 0.1 - 0.2$; in the case of GRB 090515 I do not detect any such faint galaxies within $\approx 5''$ of the afterglow position. For GRB 080503 I also include the galaxy at an offset of $0.8''$ and $m_{AB}(F606W) = 27.3 \pm 0.2$ mag identified by Perley et al. (2009) based on their deeper stack of HST observations. On the other hand, for 4 of the 5 bursts I find that the galaxies with the lowest probability of chance coincidence, $\approx 0.03 - 0.15$, are brighter objects with offsets of about $6 - 16''$ from the burst positions; only in the case of GRB 080503 the lowest chance coincidence is associated with the nearest galaxy (see (Perley et al., 2009)).

The use of *a posteriori* probabilities to assign *unique* galaxy associations is fraught with difficulties. First, for a given apparent brightness, galaxies located further away from the GRB position, potentially due to larger kicks and/or longer merger timescales in the NS-NS merger framework, have higher probabilities of chance coincidence. Since no *a priori* model-independent knowledge is available for the range of possible kicks and merger timescales, it is not possible to rule out galaxies at very large offsets for which $P(< \delta R) \sim 1$. Indeed, a reasonable constraint of $v_{\text{kick}} \lesssim 10^3 \text{ km s}^{-1}$ and $\tau_{\text{merger}} \lesssim 10 \text{ Gyr}$ leads to only a weak constraint on the offset of $\lesssim 10 \text{ Mpc}$. At $z = 0.1$ ($z = 1$) this corresponds to about 1.5° (0.3°), a pro-

jected distance at which nearly all galaxies will have a chance coincidence probability of order unity. However, this fact only means that we cannot rule out offsets that are even *larger* than inferred from the most likely host association.

A second difficulty is that I am using angular offsets, which ignore the potential wide range of redshifts (and by extension also luminosities) of the various galaxies. For example, if the faint galaxies with small offsets are located at $z \gtrsim 1$, the corresponding physical offsets are ~ 15 kpc, while if the galaxies at $\sim 10''$ offsets are located at $z \sim 0.3$, the offsets are only somewhat larger, ~ 30 kpc. A galaxy at an even lower redshift, $z \sim 0.1$, with an offset of 50 kpc will be located about $30''$ from the GRB position and incur a large penalty in terms of chance coincidence probability. It is important to note, however, that galaxies at lower redshift will generally have brighter apparent magnitudes, partially compensating for the larger angular separations (Equations 3 and 4). In only a single case (GRB 070809) I find a galaxy with $P(< \delta R) \lesssim 0.1$ at $\delta R \gtrsim 1'$ (which at $z = 0.043$ for this galaxy corresponds to a physical offset of about 100 kpc).

A final complication, which is not unique to this subset of events, is that only projected offsets can be measured, $\delta R = \delta R_{3D} \times \cos(\theta)$. The measured offsets can be used as lower limits on the actual offsets, while for the overall distribution it is possible to apply an average correction factor of $\pi/2$, based on the expectation value for the projection factor, $\cos(\theta)$.

Despite these caveats, it is possible to address the probability that *all* of the associations are spurious. This joint probability is simply the product of the individual probabilities (Bloom et al., 2002). For the faint galaxies at small angular separations the probability that all are spurious is $P_{\text{all}} \approx 8 \times 10^{-5}$, while for the galaxies with the lowest probability of chance coincidence the joint probability is nearly 30 times lower, $P_{\text{all}} \approx 3 \times 10^{-6}$. Conversely, the probabilities that *none* of the associations are spurious are ≈ 0.42 and ≈ 0.59 , respectively. These values indicate the some spurious coincidences may be present in *Sample 2*. Indeed, the probabilities that 1, 2, or 3 associations are spurious are [0.40, 0.15, 0.027] and [0.34, 0.068, 0.006], respectively. These results indicate that for the faint galaxies it is not unlikely that 2–3 associations (out of 5) are spurious, while for the brighter galaxies 1–2 associations may be spurious. This analysis clearly demonstrates why a joint statistical study is superior to case-by-case attempts to associate short GRBs with galaxies at substantial offsets.

Based on the possibility of association with the galaxies at separations of $\sim 10''$, I obtained redshift for three of these galaxies (Berger, 2010), leading to a star forming galaxy at $z = 0.111$ (GRB 061201), an early-type galaxy at $z = 0.473$ (GRB 070809), and an early-type galaxy at $z = 0.403$ (GRB 090515). The fainter host at separations of a few arcsec likely reside at $z \gtrsim 1$. The redshifts provide an indication of the physical projected offsets (§6.2).

6.1. Undetected Faint Hosts at High Redshift?

The redshifts of the GRBs in *Sample 2* can be constrained based on their detections in the optical band (i.e., the lack of strong suppression by the Ly α forest). The afterglow of

GRB 061201 was detected in the ultraviolet by the *Swift*/UVOT and it is therefore located at $z \lesssim 1.7$ (Roming et al., 2006). The remaining four bursts were detected in the optical *g*- or *r*-band, and can therefore be placed at $z \lesssim 3$ or $\lesssim 4.3$; see Berger (2010) for details.

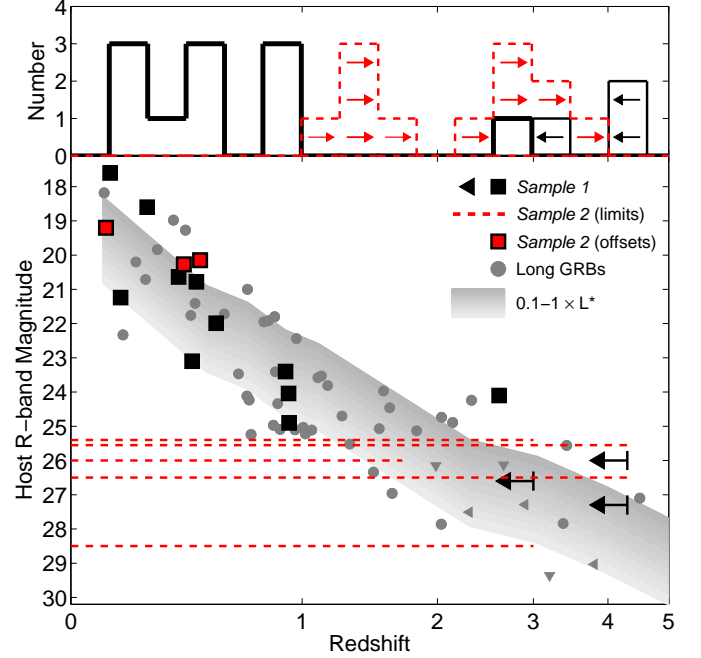


Figure 21: *Main Panel*: Host galaxy optical magnitude as a function of redshift for short GRB hosts (black squares), long GRB hosts (detections: gray circles; non-detections or no redshifts: gray triangles), and galaxies with a luminosity of $0.1-1 L^*$ (shaded region). The dashed lines mark the upper limits at the GRB positions for the short GRBs with no coincident hosts. The arrows mark the upper limits on the redshifts of three bursts in *Sample 1* with faint hosts, based on the detection of the afterglows in the optical band (i.e., lack of a strong Lyman break). If underlying host galaxies exist for *Sample 2*, their non-detection indicates $z \gtrsim 1.5$ (for $0.1 L^*$) or $\gtrsim 3$ (for L^*). The alternative possibility that they are located at similar redshifts to the detected hosts, requires $\lesssim 0.01 L^*$, but this does not naturally explain their fainter afterglows. *Upper Panel*: Projected redshift histogram for *Sample 1* (black) and *Sample 2* (dashed red limits) under the assumption that the hosts are $0.1 L^*$ galaxies ($z \sim 1.5$) and L^* galaxies ($z \sim 3$). From Berger (2010).

It is possible to place additional constraints on the redshifts of any underlying hosts using the existing sample short GRB host galaxies. In Figure 21 I plot the *r*-band magnitudes as a function of redshift for all available short GRB hosts from *Sample 1*. For the faint hosts without known redshifts (GRBs 060121, 060313, and 070707), I place upper limits on the redshift using optical detections of the afterglows. A wide range of host magnitudes, $r_{\text{AB}} \sim 16.5 - 27.5$ mag, is apparent. I also plot the *r*-band magnitudes of long GRB hosts (Savaglio et al., 2009), as well as the *r*–*z* phase space that is traced by galaxies with luminosities of $L = 0.1 - 1 L^*$. I find excellent correspondence between the hosts of long and short GRBs, and the phase-space traced by $0.1 - 1 L^*$ galaxies, at least to $z \sim 4$. In the context of these distributions, the available limits for the short GRBs in *Sample 2* translate to redshifts of $z \gtrsim 1.5$ if they are $0.1 L^*$ galaxies, or $z \gtrsim 3$ if they are L^* galaxies. The latter lower limits are comparable to the redshift upper limits inferred from

the afterglow detections. I note that for GRB 080503, the limits of $\gtrsim 28.5$ mag and $z \lesssim 3$ from the afterglow (Perley et al., 2009) place even more stringent limits on the luminosity of an underlying galaxy of $\lesssim 0.1 L^*$ galaxy.

The possibility that the five bursts originated at $z \gtrsim 3$ leads to a bimodal redshift distribution (Figure 21). Nearly all of the bursts in *Sample 1* with a known redshift (9/10) have $z \approx 0.2-1$, with a median of $\langle z \rangle \approx 0.5$; the sole exception is GRB 090426 at $z = 2.61$ (Antonelli et al., 2009; Levesque et al., 2010). The three bursts with faint coincident hosts have upper limits of $z \lesssim 4$ from afterglow detections, while lower limit of $z \gtrsim 1.5-2$ can be placed on these hosts if they have $L \gtrsim 0.1 L^*$. Adding the *Sample 2* bursts with the assumption that they have $z \gtrsim 3$ will furthermore result in a population of short GRBs with a median of $z \sim 3$, and leave a substantial gap at $z \sim 1-2$ (Figure 21). If the 5 bursts are instead hosted by $0.1 L^*$ galaxies, the inferred lower limits on the redshifts ($z \gtrsim 1.5$) lead to a potentially more uniform redshift distribution.

It is difficult to explain a bimodal redshift distribution with a single progenitor population such as NS-NS binaries, without appealing to, for example, a bimodal distribution of merger timescales. Another possibility is two distinct progenitor populations, producing bursts of similar observed properties but with distinct redshift ranges. While these possibilities are difficult to exclude, they do not provide a natural explanation for the short GRB population.

A final alternative explanation is that any underlying hosts reside at similar redshifts to the known hosts in *Sample 1* ($z \sim 0.5$), but have significantly lower luminosities of $\lesssim 0.01 L^*$. This scenario would not naturally explain why the bursts in *Sample 2* have fainter optical and X-ray afterglows, as well as lower γ -ray fluences. I therefore do not consider this possibility to be the likely explanation.

6.2. Large Offsets?

While higher redshifts may explain the lack of detected hosts, the fainter afterglows, and the smaller γ -ray fluences of the bursts in *Sample 2*, this scenario suffers from several difficulties outlined above. The alternative explanation is that the bursts occurred at significant offsets relative to their hosts, and hence in lower density environments that would explain the faint afterglow emission (though possibly not the lower γ -ray fluences). As demonstrated in the chance coincidence analysis, the offsets may be $\sim 2''$ (~ 15 kpc) if the bursts originated in the faint galaxies at the smallest angular separations, or $\sim 10''$ ($\sim 30-75$ kpc) if they originated in the brighter galaxies with the lowest probability of chance coincidence (Figure 20).

The projected physical offsets for *Sample 1* and *Sample 2* are shown in Figure 22. The mean and standard deviation for *Sample 1* are $\delta R = 4.2 \pm 3.8$ kpc, and a log-normal fit results in a mean of $\log(\delta R) \approx 0.5$ and a width of $\sigma_{\log(\delta R)} \approx 0.3$. On the other hand, the bursts in *Sample 2* have a mean offset of about 19 kpc if they arise in the faint galaxies with small angular separation, or about 40 kpc if they arise in the brighter galaxies, pointing to distinct distributions.

A similar result is obtained when considering the offset normalized by each host's effective radius, R_e (as advocated by

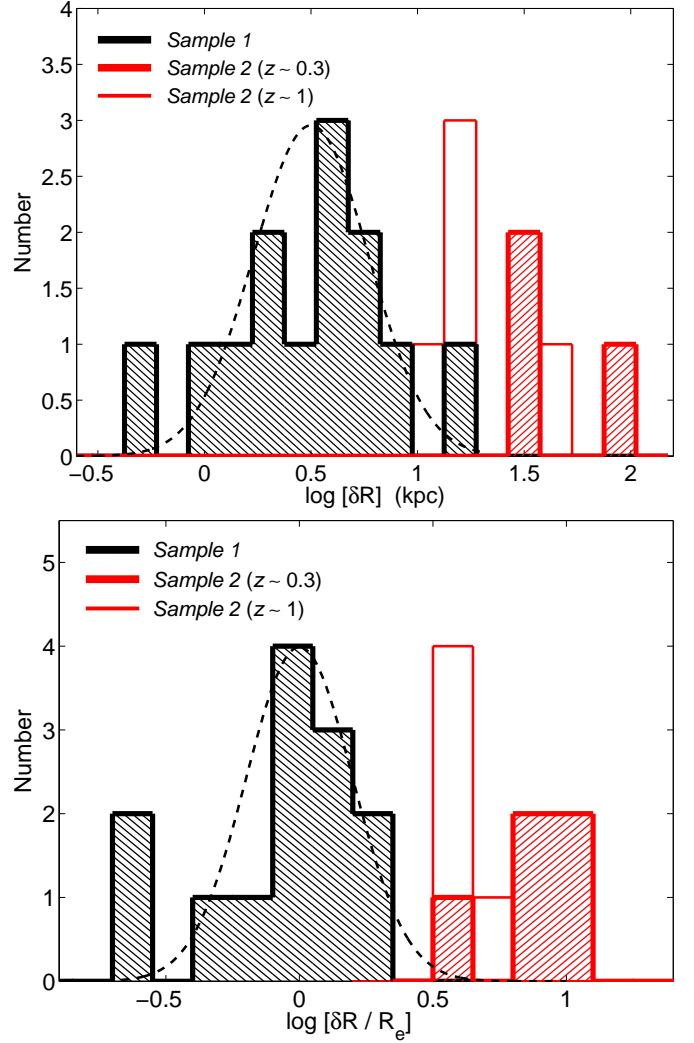


Figure 22: *Top*: Histogram of projected physical offsets relative to the host galaxy center for short GRBs with coincident hosts (hatched black), and bursts with no coincident hosts if the galaxies with lowest chance coincidence probability are the hosts (hatched red), or if the faint galaxies with smallest angular separation are hosts (open red); see Figure 20. The dashed line is a log-normal fit to the bursts with coincident hosts. *Bottom*: Same, but for offsets normalized relative to the host effective radii, R_e . The dashed line is a log-normal fit to the bursts with coincident hosts. From Berger (2010).

Fong et al. (2010)). This quantity takes into account the varying sizes of the hosts due to both intrinsic size variations and redshift effects. It also gives a better indication of whether the burst coincides with the host light or is significantly offset. As shown in Figure 22, the host-normalized offsets of *Sample 1* have a mean and standard deviation of about $1 \pm 0.6 R_e$, and a range of about $0.2 - 2 R_e$. A log-normal fit results in a mean of $\log(\delta R/R_e) \approx 0$ and a width of $\sigma_{\log(\delta R/R_e)} \approx 0.2$. The bursts in *Sample 2* have much larger host-normalized offsets, with $(\delta R/R_e) = 7.3 \pm 2.3$ if they originated in the galaxies with the lowest chance coincidence probability. Even if I associate the bursts with the nearest faint hosts, the distribution has a mean of about $4 R_e$, reflecting the fact that the effective radii of the faint galaxies are smaller than those of the brighter ones.

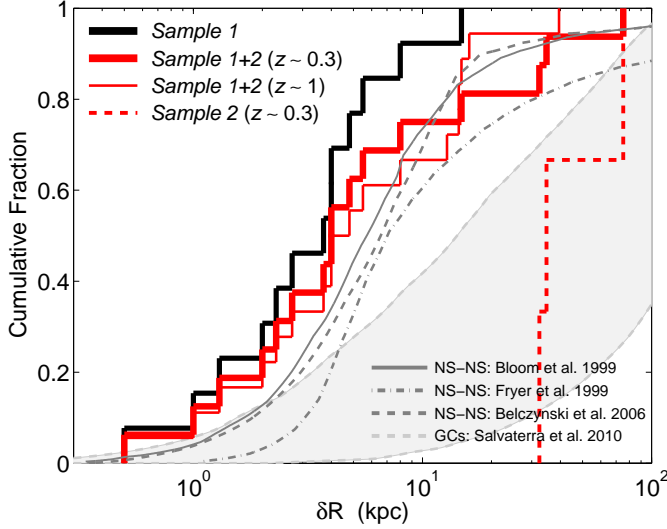


Figure 23: Cumulative distributions of projected physical offsets for short GRBs with coincident hosts (black line), and combined with offsets for the hosts with the lowest probabilities of chance coincidence (thick red line) or the faint hosts with smallest angular offsets (thin red line). Also shown are predicted distributions for NS-NS kicks from several models (Bloom et al., 1999; Fryer et al., 1999; Belczynski et al., 2006), and for dynamically-formed NS-NS binaries from globular clusters (shaded region marks a range of predictions for host galaxy masses of $5 \times 10^{10} - 10^{12} M_{\odot}$; (Salvaterra et al., 2010)). The models with kick velocities are in good agreement with the measured offset distribution for either set of galaxy associations, while the globular clusters model provides a poor match to the data. From Berger (2010).

Thus, the distributions of physical, host-normalized, and angular offsets exhibit a clear bimodality when associating the bursts in *Sample 2* with the galaxies at $z \sim 0.1 - 0.5$. The effect is still apparent, though less pronounced in the case of association with the faint galaxies at $z \gtrsim 1$. Thus, if the offset scenario is correct, the resulting distributions point to a possible bimodality rather than a single continuous distribution of offsets.

The cumulative distributions of physical offsets for *Sample 1* alone, and in conjunction with the two possible offset groups for *Sample 2* are shown in Figure 23. The combined distributions have a median of about 4 kpc, driven by the bursts with coincident hosts. However, there is a clear extension to larger physical offsets in the case of association with the brighter galaxies, with about 20% of all objects having $\delta R \gtrsim 30$ kpc. The cumulative distributions are particularly useful for comparison with NS-NS merger models since predictions exist for both the kick scenario and the globular cluster origin model.

7. Implications for the Progenitors

The extensive analysis of host galaxy properties and the sub-galactic environments of short GRBs presented above provides important insight into the nature of the progenitors. I address in particular the popular NS-NS merger model, as well as delayed magnetar formation via WD-WD mergers or WD accretion-induced collapse (Metzger et al., 2008).

7.1. Host Galaxy Demographics and Properties

The identified hosts of short GRBs with sub-arcsecond positions (generally from optical afterglows) are dominated by star-forming galaxies with a ratio of about 4:1, although I note that the nature of the hosts of several short GRBs with sub-arcsecond positions remain unknown mainly due to their faintness and/or lack of deep imaging and spectroscopic observations. Only if all the unidentified hosts are early-type galaxies, would we have a ratio of 1:1. The putative hosts identified in coincidence with XRT error circles exhibit a similar ratio of about 4:1. This result is also supported by the morphological analysis of short GRB hosts observed with *HST* (Fong et al., 2010), which indicates that the ratio of hosts with an exponential disk profile versus a de Vaucouleurs profile is 4:1. Thus, I conclude that the most conservative estimate of the ratio of star forming to elliptical hosts is about 1:1, but that if the well-studied (i.e., brighter) hosts are representative of the whole sample, then the ratio is about 4:1. A ratio of about 1:1 is expected if short GRBs select galaxies by stellar mass alone. Thus, the existing demographics cannot rule out this scenario, but do appear to point to an over-abundance of short GRBs in late-type galaxies, possibly indicative of a short GRB rate that partially depends on star formation activity.

Although star forming hosts appear to dominate the host population, it is clear from a comparison of their luminosities, metallicities, stellar masses, population ages, sizes, and star formation rates that they are distinct from the hosts of long GRBs. Namely, they exhibit lower star formation activity and appear to be larger, more massive, and dominated by more evolved stellar populations. This indicates that the short GRB progenitors are mostly related to the old stellar populations within their hosts, and perhaps only partially to the modest level of on-going star formation activity. This is further supported by the dearth of morphological galaxy merger signatures, which point to delays of $\gtrsim 1$ Gyr relative to any merger-triggered star formation episodes. These conclusions are in direct contrast to the massive star progenitors of long GRBs, which select galaxies by star formation (and perhaps metallicity). While the relation to old stellar populations does not rule out models such as WD-WD mergers or WD/NS AIC, it does disfavor young magnetars.

As an aside, I note that this result demonstrates that caution should be taken with the proposed re-classification of short and long GRBs into Type I and II events, marking old and young progenitors, respectively (Zhang et al., 2007, 2009). Such a new bimodal classification may lead to the erroneous conclusion that short GRBs in late-type galaxies (even if they track the on-going star formation activity) share the same progenitors as long GRBs (e.g., (Virgili et al., 2009)) since both would be classified as Type II. At the very least, such a new classification scheme may require a further breakdown of the Type II events into those that result from massive stars versus those that simply track star formation activity with a modest delay, e.g., Type IIa and IIb. Clearly, this is beyond the scope of the current short GRB sample.

In the context of the NS-NS/NS-BH merger models, the host demographics, coupled with the redshift distribution,

provide a rough constraint on the typical merger time delay (Guetta and Piran, 2006; Nakar et al., 2006; Berger et al., 2007; Zheng and Ramirez-Ruiz, 2007). In the formulation of Zheng and Ramirez-Ruiz (2007), with a merger timescale probability distribution of $P(\tau) \propto \tau^n$, the dominance of star forming hosts with a ratio of about 4:1 indicates $n \lesssim -1$. I note that this is only a rough estimate since the calculation is appropriate for $z \sim 0$, while the host redshift distribution extends at least to $z \sim 1$. Similarly, a comparison of the observed redshift distribution (with a range of $z \sim 0.2 - 2$ and a median of ~ 0.7) to the models of Nakar et al. (2006) (their Figure 2), indicates a typical progenitor merger timescale of about 3 Gyr (for a log-normal merger timescale distribution). A comparison to the models of Guetta and Piran (2006) (their Figure 4), indicates a value of $n \sim -1$ (for a power law merger timescale distribution), in good agreement with the results from host demographics.

Thus, I conclude that based on the nature of short GRB host galaxies and their redshift distribution, the merger timescale distribution for the NS-NS/NS-BH coalescence models can be characterized by a power law index of ~ -1 (power law model) or a typical value of ~ 3 Gyr (log-normal model). If the subset of short GRBs in late-type galaxies tend to track star formation activity, their typical progenitor ages are instead ~ 0.2 Gyr (Leibler and Berger, 2010). It should be noted that the merger timescale distribution for the admittedly small sample of Galactic NS-NS binaries has been claimed to be ~ -1 (Piran, 1992; Champion et al., 2004).

7.2. Short GRB Offsets

The differential offsets measured from the *HST* observations provide the most precise values to date for short GRBs, with a total uncertainty of only $\sim 10 - 60$ mas ($\lesssim 1$ pixel), corresponding to $\sim 30 - 500$ pc. None of the offsets are smaller than ~ 1 kpc, while this is the median offset for long GRBs. On the other hand, a substantial fraction of the offsets are only a few kpc, indicating that at least some short GRBs explode within the stellar component of their hosts (rather than their extended halos). The median offset from the *HST* observations supplemented by ground-based data is about 5 kpc (Figure 16), roughly 5 times larger than for long GRBs.

As discussed above, the observed offset distribution is incomplete since about $1/4 - 1/3$ of all short GRBs have only γ -ray positions ($\sim 1 - 3'$), and a similar fraction have only XRT positions, which generally lead to a range of $\sim 0 - 30$ kpc. Taking these limitations into account I find that the most robust constraints on the offset distribution are that $\gtrsim 25\%$ of all short GRBs have offsets of $\lesssim 10$ kpc, and that $\gtrsim 5\%$ have offsets of $\gtrsim 20$ kpc. In addition, for the current sample of short GRBs with sub-arcsecond afterglow positions and no coincident bright hosts, I find evidence for offsets of ~ 50 kpc (§6).

Both the observed offset distribution and the various constraints are in good agreement with predictions for the offset distribution of NS-NS binaries in Milky Way type galaxies (Bloom et al., 1999; Fryer et al., 1999; Belczynski et al., 2006). However, at the present a partial contribution from other progenitor systems, such as delayed magnetar formation and even

young magnetar flares, cannot be ruled out. The existence of modest (~ 10 kpc) and perhaps large (~ 50 kpc) offsets in the sample suggests that these latter models are not likely to account for *all* short GRBs.

In the context of implications for the progenitor population, the study of short GRB physical offsets by Troja et al. (2008) led to the claim that short GRBs with extended X-ray emission have systematically smaller offsets than those with only a prompt spike, possibly due to a systematic difference in the progenitors. The *HST* sample of Fong et al. (2010) includes three short GRBs with significant extended emission (050709, 050724, and 061006), and one burst (060121) with possible extended emission (4.5σ significance; (Donaghy et al., 2006)). The physical offsets of these bursts are about 3.7, 2.7, 1.3, and 1 kpc, respectively, leading to a mean offset of about 2.2 kpc. The physical offsets of the bursts without extended emission, but with precise afterglow positions (051221, 060313, and 061201) are 2.0, 2.3, and 14.2 or 32.5 kpc, respectively. The two events with no extended emission and with XRT positions (050509B and 051210) have offsets of about 54 ± 12 and 28 ± 23 kpc, respectively. Including the ground-based sample with optical afterglow positions, the bursts with apparent extended emission (070714B, 071227, 080513, and 090510; (Barbier et al., 2007; Sakamoto et al., 2007; Ukwatta et al., 2009; Perley et al., 2009)) have offsets of $\lesssim 4$, 14.8, ~ 20 , and ~ 5.5 kpc, while the bursts without extended emission (070724 and 070809) have offsets of 4.8 and ~ 6.5 kpc. Thus, in the sample of events with sub-arcsecond positions, 6/8 bursts with extended emission have offsets of $\lesssim 5$ kpc and 2/8 have likely offsets of $\sim 15 - 20$ kpc. In the sample without extended emission, 4/5 have offsets of $\lesssim 6$ kpc and 1/5 has a likely offset of $\sim 14 - 32$ kpc. Thus, at the present it does not appear that there is a significant difference in the two offset distributions.

The inclusion of events with only XRT positions does not alter this conclusion. In particular, of the subset with no extended emission only GRB 050509B is likely to have a significant offset, while GRBs 051210, 060801, and 070429B have offsets (28 ± 23 , 19 ± 16 , and 40 ± 48 kpc, respectively) that are consistent with zero. Similarly, GRB 061210 with extended emission has an offset of 11 ± 10 kpc. A continued investigation of the difference between short GRBs with and without extended emission will greatly benefit from the use of host-normalized offsets, which take into account the individual hosts' effective radii.

7.3. Large Offsets?

The sample of short GRBs with optical afterglows represents about $1/3$ of all short bursts, and may thus not be fully representative. One often-discussed bias is that the bursts with optical afterglows require a high circumburst density, and therefore have negligible offsets. However, from the analysis in §6 (Berger, 2010) it is clear that one explanation for the lack of coincident hosts for the bursts in *Sample 2* is indeed large offsets, *despite their detection in the optical band*.

As shown in Figure 23, the NS-NS merger model predictions have a median of about 6 kpc, compared to about 4 kpc for the observed sample. On the other hand, the models predict

10 – 20% of offsets to be $\gtrsim 30$ kpc, in good agreement with the observed distribution in both the ~ 15 kpc and ~ 40 kpc scenarios (§6). I note that the overall smaller offsets measured from the data may be due to projections effects. Indeed, the mean correction factor of $\pi/2$ nicely reconciles the theoretical and observed distributions.

In §6 I noted a bimodality in the physical and host-normalized offsets for *Sample 1* and *Sample 2* (Figure 22). In the framework of NS-NS binary kicks this bimodality may indicate that the binaries generally remain bound to their host galaxies, thereby spending most of their time at the maximal distance defined by $d_{\max} = 2GM_{\text{host}}/v_{\text{kick}}^2$ (i.e., with their kinetic energy stored as potential energy; (Bloom et al., 2007)). This would require typical kick velocities of less than a few hundred km s⁻¹.

I further compare the observed offset distribution to predictions for dynamically formed NS-NS binaries in globular clusters, with a range of host galaxy virial masses of $5 \times 10^{10} - 10^{12} M_{\odot}$ (Salvaterra et al., 2010). These models predict a range of only $\approx 5 - 40\%$ of all NS-NS mergers to occur within 10 kpc of the host center, in contrast to the observed distribution with about 70% with $\delta R \lesssim 10$ kpc. I stress that this result is independent of what offsets are assigned to the bursts in *Sample 2* since they account for only 1/4 of the bursts with optical afterglows. On the other hand, the globular cluster origin may account for the bimodality in the physical and host-normalized offsets (Figure 22), with the objects in *Sample 2* arising in globular clusters and the objects with coincident hosts arising from primordial NS-NS binaries. This possibility also agrees with the predicted fraction of dynamically-formed NS-NS binaries of $\sim 10 - 30\%$ (Grindlay et al., 2006). The cumulative offset distributions for *Sample 2* alone (assuming the hosts are the galaxies with the lowest probability of chance coincidence) is well-matched by the range of predictions for dynamically-formed NS-NS binaries in globular clusters (Figure 23). In this scenario, however, the implication is that short GRBs outside of globular clusters do not experience kicks as expected for NS-NS binaries since the largest measured offset is only 15 kpc.

Unless the populations of short GRBs with only X-ray or γ -ray positions have fundamentally different offset distributions, I conclude that the measured offsets of short GRBs and the predicted offsets for NS-NS kicks are in good agreement, *if when treating all short GRBs with optical afterglows as a single population*. Alternatively, it is possible that the bimodal distributions of physical and host-normalized offsets point to a progenitor bimodality, with the bursts in *Sample 2* originating in globular clusters.

7.4. Relation to the Host Galaxy Light Distribution

In addition to the projected offsets relative to their host centers, it is apparent that short GRBs are more diffusely distributed relative to their host light than long GRBs. In particular, the locations of short GRBs under-represent their overall host light distributions, even in comparison to core-collapse and Type Ia SNe. On the other hand, it appears from the current small sample that short GRBs are better tracers of their

hosts' rest-frame optical light than UV light. This result indicates that short GRBs arise in locations within their hosts that trace the distribution of older stellar populations, and clearly do not trace the sites of active star formation. This result provides strong support to the claim that although most short GRB hosts are star forming galaxies, the bursts themselves are not related to the star formation activity (§3).

At the present, the sample of events with sufficiently precise astrometry to determine the burst locations at the level of $\lesssim 1$ *HST* pixel is very small (6 events). It is therefore not possible to draw conclusions about the fraction of short GRBs that are associated with old stellar populations as opposed to young populations (as expected for young magnetars). Luckily, there are at least 10 additional events for which these measurements can be made with future *HST* observations. At the present, I conclude that the stronger correlation of short GRBs with the rest-frame optical light than UV light of their hosts is indicative of a dominant old progenitor population.

8. Conclusions

While the sample of short GRBs with afterglow positions is still significantly smaller than that of long GRBs, we have made significant progress in understanding their galactic and sub-galactic environments. The results of host galaxy imaging and spectroscopy, including high-resolution imaging with *HST*, point to an association of short GRBs with old stellar populations within a range of normal star forming and elliptical galaxies. In nearly every respect (star formation rates, metallicities, sizes, offsets, light distribution) the environments of short GRBs are distinct from those of long GRBs, indicating that their progenitors are not related to a young progenitor population.

As I showed through the study of short GRB offsets, host galaxy demographics, and the redshift distribution, the current observations are fully consistent with NS-NS/NS-BH binary mergers. However, a partial contribution from other (mainly old) progenitor channels (e.g., WD-WD mergers leading to magnetar formation, WD/NS AIC) cannot be ruled out at the present. Currently, we do not have conclusive evidence for significant progenitor kicks, which are only expected in the coalescence model. Still, a few events with sub-arcsecond optical positions do not directly coincide with bright host galaxies, and yet reside within tens of kpc from bright, low-redshift galaxies. This may be suggestive of progenitor kicks, but it is also possible that these bursts are associated with fainter hosts (likely at higher redshift) with marginal offsets.

With continued vigilance, and a short GRB discovery rate of about 1 event per month, we are likely to gain further insight into the nature of short GRB progenitors in the next few years, possibly with the first detections (or significant limits) of gravitational waves. As argued in this review, host galaxy observations of existing and future events will play a central role in our on-going quest to determine the identity of short GRB progenitors.

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